

# **Thermal Battery Operating Gas Atmosphere Control and Heat Transfer Optimization**

**by Frank C. Krieger and Michael S. Ding**

**ARL-TR-6156**

**September 2012**

## **NOTICES**

### **Disclaimers**

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# **Army Research Laboratory**

Adelphi, MD 20783-1197

---

---

**ARL-TR-6156**

**September 2012**

---

## **Thermal Battery Operating Gas Atmosphere Control and Heat Transfer Optimization**

**Frank C. Krieger and Michael S. Ding**  
**Sensors and Electron Devices Directorate, ARL**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY) September 2012		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Thermal Battery Operating Gas Atmosphere Control and Heat Transfer Optimization				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Frank C. Krieger and Michael S. Ding				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-SED-C 2800 Powder Mill Road Adelphi, MD 20783-1197				8. PERFORMING ORGANIZATION REPORT NUMBER  ARL-TR-6156	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>The effects of gases and gas mixtures on global thermal conductivity values of porous thermal insulation packages of fully assembled Low Cost Competent Munition (LCCM) thermal batteries using transient and quasi-steady-state heat transfer techniques are reported. These results show that the volumetric energy densities of most presently fielded munitions thermal batteries can be increased by factors ranging from 1.5 to 3 if hydrogen gas can be removed. Zirconium (Zr) based gas getters are highly effective in atmospheres of pure hydrogen and are potentially useful in mixtures of hydrogen and air. Barium chromate (BaCrO<sub>4</sub>) placed in contact with heat paper made from Zr/BaCrO<sub>4</sub> heat powder forms an effective oxidizing ash for hydrogen gas when the heat paper is ignited. Because the oxidizing ash is not present until the battery is initiated there is no need to protect a chemically active surface during the required 20-year storage lifetime. Water formed from the hydrogen/oxidizing ash reaction did not react to form additional hydrogen during LCCM thermal battery operation.</p>					
15. SUBJECT TERMS Thermal battery, thermal conductivity, hydrogen gas removal, gas gettering, thermal modeling					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES  70	19a. NAME OF RESPONSIBLE PERSON Frank C. Krieger
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (301) 394-3115

---

## Contents

---

List of Tables	v
Acknowledgments	vii
1. Introduction	1
2. Experimental	2
3. Experimental Global LCCM Thermal Insulation Package Thermal Conductivity Values	3
4. Hydrogen Removal by Oxidation with Barium Chromate	6
5. Hydrogen Gas Gettering	11
6. Thermal Modeling	16
7. Summary and Conclusions	17
8. References	19
Appendix A. Measured Global Thermal Conductivity Values for the LCCM Thermal Insulation Package	21
Appendix B. Hydrogen Oxidation by Barium Chromate	47
Appendix C. Testing of Zr-based Gas Getters	53
Distribution List	58

---

## List of Figures

---

Figure 1. Measured global thermal conductivity values for the LCCM thermal insulation package in selected gas atmospheres. Legend numbers are nominal gas pressures in absolute atmospheres. Three of the four curves that include data above 60 °C are quasi-steady-state data from two operating LCCM thermal batteries and from the copper-heat pellet stack using the LCCM thermal insulation package. For low thermal conductivity gases, heat losses through the solid portions of the thermal insulation package become more significant. ....	4
Figure 2. Measured global thermal conductivity values for the LCCM thermal insulation package in air at nominal pressures of 1 and 7 atmospheres absolute and in hydrogen at nominal pressures of 1 and 9 atmospheres absolute. ....	6
Figure 3. Modified gas handling system. The filters are 0.5 $\mu$ . ....	7
Figure 4. Gas evolution test for LCCM flight test heat paper. The constant pressures at ~314, ~270, and ~6.9 Torr with MV2 open strongly suggest that the ash is not reacting significantly with the gas at those pressures. The nearly equal gas volumes at ~314, ~270, and ~6.9 Torr, combined with the chromatographic analyses, show that little or no water vapor was formed during the experiment. ....	8
Figure 5. Gas evolution test for LCCM flight test heat paper in physical contact with barium chromate. Pressure decreases starting at ~42 and at ~35 Torr during the test show a reaction of the ash with the gas atmosphere. ....	9
Figure 6. Gas getter tests in pure hydrogen (full pressure range). ....	13
Figure 7. Gas getter tests in pure hydrogen (low pressure range). ....	14
Figure 8. Gas getter tested in pure hydrogen as received and after 700 °C heating under helium (low pressure range). ....	15
Figure 9. Gas gettering from a 79.6/20.4 volume percent hydrogen/air mixture. ....	16
Figure A-1. LCCM global thermal insulation package thermal conductivity values for helium at 10 atmospheres absolute, for hydrogen at 9 atmospheres and at 1 atmosphere absolute, and for a 33/67 volume percent hydrogen/air mixture at 8 atmospheres absolute. ....	41
Figure A-2. LCCM global thermal insulation package thermal conductivity values for a fore pump vacuum atmosphere (~6.7 Pa), for a 33/67 volume percent hydrogen/air mixture at 1 atmosphere absolute, for argon at 1 atmosphere absolute, and for xenon at 8 atmospheres absolute. ....	42
Figure A-3. LCCM global thermal insulation package thermal conductivity values for air at one atmosphere absolute, for pure hydrogen at 11 atmospheres absolute as measured using the copper-heat pellet high temperature transient experiment, for the LCCM thermal battery GPS9Q quasi-steady-state experiment, hermetically sealed containing 1 atmosphere of dry room air and then initiated as the cell stack cooled from nominally 550 °C to -40 °C, and for a the copper-heat pellet stack quasi-steady-state experiment built into an LCCM configuration as the copper disks cooled from nominally 500 °C to -40 °C in a fore pump vacuum. ....	43

Figure A-4. LCCM global thermal insulation package thermal conductivity values for xenon at 1 atmosphere absolute, for xenon at 0.5 atmosphere absolute, for air at 7 atmospheres absolute, and for the LCCM thermal battery GPS9P quasi-steady-state experiment as the cell stack cooled from nominally 550 °C to −40 °C in a fore pump vacuum as described in reference 1. The Xe.5 heating curve appears to become increasingly contaminated with higher thermal conductivity gases as it approaches 60 °C near the end of the experiment. ....	44
Figure B-1. Gas evolution of LCCM flight test heat paper.....	47
Figure B-2. Gas evolution from LCCM flight test heat paper. ....	48
Figure B-3. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO <sub>4</sub> . ....	49
Figure B-4. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO <sub>4</sub> . ....	50
Figure B-5. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO <sub>4</sub> . ....	51
Figure C-1. Hydrogen gas gettering from a pure hydrogen atmosphere. ....	54
Figure C-2. Gas gettering from a hydrogen/air mixture.....	55
Figure C-3. Gas gettering from a hydrogen/air mixture.....	56

---

## List of Tables

Table 1. Oxidation of hydrogen gas evolved from LCCM heat paper using BaCrO <sub>4</sub> . ....	11
Table A-1. Tabular global thermal conductivity values for the LCCM thermal insulation package. Thermal conductivity values are shown in cal/s-cm-°C. ....	45
Table A-2. Tabular global thermal conductivity values for the LCCM thermal insulation package. Thermal conductivity values are shown in cal/s-cm-°C. ....	46

INTENTIONALLY LEFT BLANK.



---

## Acknowledgments

---

This work was funded by a Picatinny/Armament Research, Development and Engineering Center (ARDEC) Technical Program Annex (TPA) under the supervision of Jason Devenezia.

Anne Grillet and Ed Piekos of the Sandia National Laboratories in Albuquerque, NM, provided much knowledgeable assistance on the Sierra thermal battery heat transfer model.

Martha Given and Joel Biddier of the U.S. Army Research Laboratory (ARL/ADELPHI MD) “zteam” provided valuable Unix support for the Fortran and Sierra finite element programs.

Richard Kullberg of Vacuum Energy Inc. in Shaker Heights OH provided his extensive technical expertise and advice, as well as zirconium-based gas getter material for testing.

INTENTIONALLY LEFT BLANK.

---

## 1. Introduction

---

The primary thermal reserve batteries used in munitions are highly reliable one-time-use-only power sources with typical lifetimes of 5 min or less and required shelf lives of as long as 20 years that are assembled into bombs and missile or artillery rounds during manufacture. The batteries are hermetically sealed and have high operating voltaic cell temperatures (400–600 °C). The batteries are typically activated simultaneously with the ordnance device by heating the electrochemical cells to their operating temperature using a fixed amount of pyrotechnic material. The electrochemical cells then become active and the electrochemical-heat-source stack begins to cool through a thermal insulation package.

As presently manufactured, these batteries are ordinarily heat limited and contain excess active electrochemical material, which also serves as an internal heat reservoir. When the batteries are heat limited, the electrochemical cells simply cool below their required operating temperature before the available electrochemical lifetime can be supplied. Because extra electrochemical material is already present, simply reducing heat loss rates can increase battery lifetimes for many fielded applications.

For munitions thermal reserve batteries, the emphasis is usually on volume reduction rather than on weight reduction. Control of the operating atmosphere gas quantities and chemical compositions, when used with mathematical modeling, can increase the volumetric energy densities (reducing the required sizes) of most presently fielded munitions thermal battery applications by factors ranging from 1.5 to 3 (1–3). High thermal conductivity hydrogen gas evolved during battery initiation and operation can be removed by the oxidation of hydrogen gas to water or by gas gettering methods.

The oxidizing ash of zirconium (Zr)/barium chromate ( $\text{BaCrO}_4$ ) heat powders with low Zr percentages (~21/79 w/o (weight percent) Zr/ $\text{BaCrO}_4$ ) has long been known to produce small quantities of hydrogen gas (4). The reducing ash formed from Zr/ $\text{BaCrO}_4$  powders with high percentages of Zr (~28/72 w/o Zr/ $\text{BaCrO}_4$ ), by contrast, has long been known to produce large quantities of hydrogen gas. This suggests that  $\text{BaCrO}_4$  could be processed into or placed in contact with existing heat paper powder formulations where it would oxidize hydrogen gas and form water when the heat paper is initiated. The resulting Zr/ $\text{BaCrO}_4$  powder mixtures could then serve as low-cost, previously well-characterized, readily available hydrogen gas oxidizing agents in presently fielded thermal batteries.

Operating gas atmosphere chemical composition tests have shown that water liquid and vapor present in the operating Low Cost Competent Munition (LCCM) thermal reserve battery did not react with chemically active battery components to produce significant quantities of hydrogen gas (1, 2, 5). It should be noted, however, that LCCM had a massive outer case that remained near

–40 °C during battery operation. The possible extent of this reaction must be investigated more thoroughly, especially for thermal batteries with higher case operating temperatures. Traditional methods of gas control, including materials selection, chemical processing, internal heat balancing, and internal construction methods, should be used initially, so that hydrogen gas oxidation or gettering need remove only a minimal amount of hydrogen.

Because the lifetimes of munitions thermal reserve batteries are short (typically 1 to 3 min), any hydrogen gas evolved during battery initiation and operation must be removed rapidly. Hydrogen gas can be removed quickly both by oxidation using BaCrO<sub>4</sub> heated to high temperatures with heat papers or powders and by using gas getters. Zr-based gas getters can remove hydrogen gas rapidly from atmospheres of pure hydrogen. Zr-based gas getters are less efficient, but are still usable in hydrogen/air gas mixtures. Only small quantities (1 to 3 g for LCCM) of either BaCrO<sub>4</sub> or Zr-based gas getter material (easily incorporated into the battery during manufacture) are needed to remove the required quantities of hydrogen gas (~50 std-atm-cc or 4.50 mg of H<sub>2</sub> for LCCM).

Present munitions thermal reserve batteries are hermetically sealed in dry room air at a dew point of –40 °C or lower during manufacture. Measurements of operating thermal reserve battery gas atmosphere chemical compositions show that the complete removal of hydrogen gas from those batteries, combined with appropriate thermal modeling and optimization, can reduce global thermal insulation conductivity values (and thereby increase the electrical lifetimes) by factors ranging from 1.5 to 3. Measured global thermal conductivity values and thermal models show that even partial removal of the hydrogen gas can produce significant increases in the volumetric energy densities (size reduction) of munitions thermal batteries. Significantly greater improvement is possible by backfilling the batteries with low thermal conductivity gases such as argon (Ar), krypton (Kr), and xenon (Xe), but the focus of this report is on the removal of high thermal conductivity hydrogen gas from presently fielded thermal batteries. The reaction rates of gas getters with mixtures of hydrogen and inert gases such as Ar, Kr, or Xe, and of hydrogen gas with small quantities of commonly encountered thermal battery gas atmosphere contaminants (O<sub>2</sub>, N<sub>2</sub>, CO, CH<sub>4</sub>, and CO<sub>2</sub>) will be investigated in the near future.

---

## **2. Experimental**

---

Gas evolution and LCCM thermal conductivity measurements and analyses were done as described previously (2, 5), using an Agilent 34970A Data Acquisition/Switch Unit (typically 10 readings/s), MKS Baratron dual capacitance manometer pressure transducers, an Agilent 7890A gas chromatograph with a thermal conductivity detector, and type K thermocouples. A stainless steel (SS) tube was used as a chemical reaction vessel for the gas gettering experiments. The SS tube was heated using a Lindberg/Blue M model number TF55035A–1 tube furnace from

Thermo Fisher Scientific (maximum operating temperature 1100 °C). The SS tube was enclosed in a protective quartz tube to insure proper operation of the tube furnace.

Chemicals were processed in the U.S. Army Research Laboratory (ARL)/Adelphi dry room at a nominal dew point of  $-56\text{ }^{\circ}\text{C}$  (0.074% relative humidity at 70 °F). ARL processed and purchased chemicals were dried in a Yamato ADP 21 Vacuum Drying Oven using a Model RVT 400 – 115 Refrigerated Vapor Trap from Thermo Electric Corporation (nominal cold trap temperature  $-50\text{ }^{\circ}\text{C}$ ) and a Uniweld UVP4 vacuum pump that could deliver a minimum pressure of nominally 50 microns of mercury (6.7 Pa). Most heat papers, heat powders, and gas getters used were from commercial vendors, or were fabricated in-house at ARL/Adelphi. One of the older (ca. 1960) Zr/BaCrO<sub>4</sub> heat powders originally came from the old National Bureau of Standards in Washington D.C., and showed similar gas evolution properties to those previously reported (4), as expected. Chemicals were weighed using an AWS AL-201S Analytical Balance or a Mettler Toledo AT 20 Microbalance. The BaCrO<sub>4</sub> used was certified grade from Fisher Scientific. Global measured leak rates of the entire evacuated gas handling system, as used in the various experiments, were typically measured by pressure readings taken over periods of several days or weeks and ranged from  $5.3\text{ E}-5$  to  $6.3\text{ E}-6$  std-atm-cc/s.

A schematic of the previously reported modified gas handling system used is included in this report to facilitate an understanding of the gas volume measurements (1, 2). All of the gas and gas handling system volumes were measured relative to the volume of the 10-cc sample bottle, using the ideal gas law. The 10-cc sample bottle volume was accurate to  $\pm 10\%$ . Absolute gas quantities were therefore measured to an accuracy of approximately  $\pm 10\%$ . Relative gas quantities, however, and gas volumes relative to the 10-cc sample bottle, could be measured to a precision of better than  $\pm 0.1\%$  using the dual capacitance manometers. Relative hydrogen quantities could be measured to an accuracy of better than  $\pm 0.1\%$  if the gas measured was known to be pure hydrogen.

---

### **3. Experimental Global LCCM Thermal Insulation Package Thermal Conductivity Values**

---

Global thermal conductivity values of the thermal insulation package of fully assembled LCCM thermal batteries were measured in various gas atmospheres using quasi-steady-state and transient heat transfer methods as previously described in reference 1. The lowest thermal conductivity components of that thermal insulation package consist mostly of finely divided silica particles along with other finely divided particles such as titanium dioxide to reduce radiation heat transfer. A large portion of these low thermal conductivity thermal insulators (~90 v/o [volume percent]) is simply void volume that will be ordinarily be filled with the gas that is in the surrounding atmosphere. Radiation and convection heat transfer through these lowest thermal conductivity thermal insulators (and through the entire LCCM thermal insulation

package) are both minimal. The measured thermal conductivity values from the cooling curves of this report can be used directly to determine the total amount of heat lost through the LCCM thermal insulation package at the reported thermal insulation package temperatures as explained in appendix A and reference 1. Representative results of those thermal conductivity measurements are shown in figure 1.

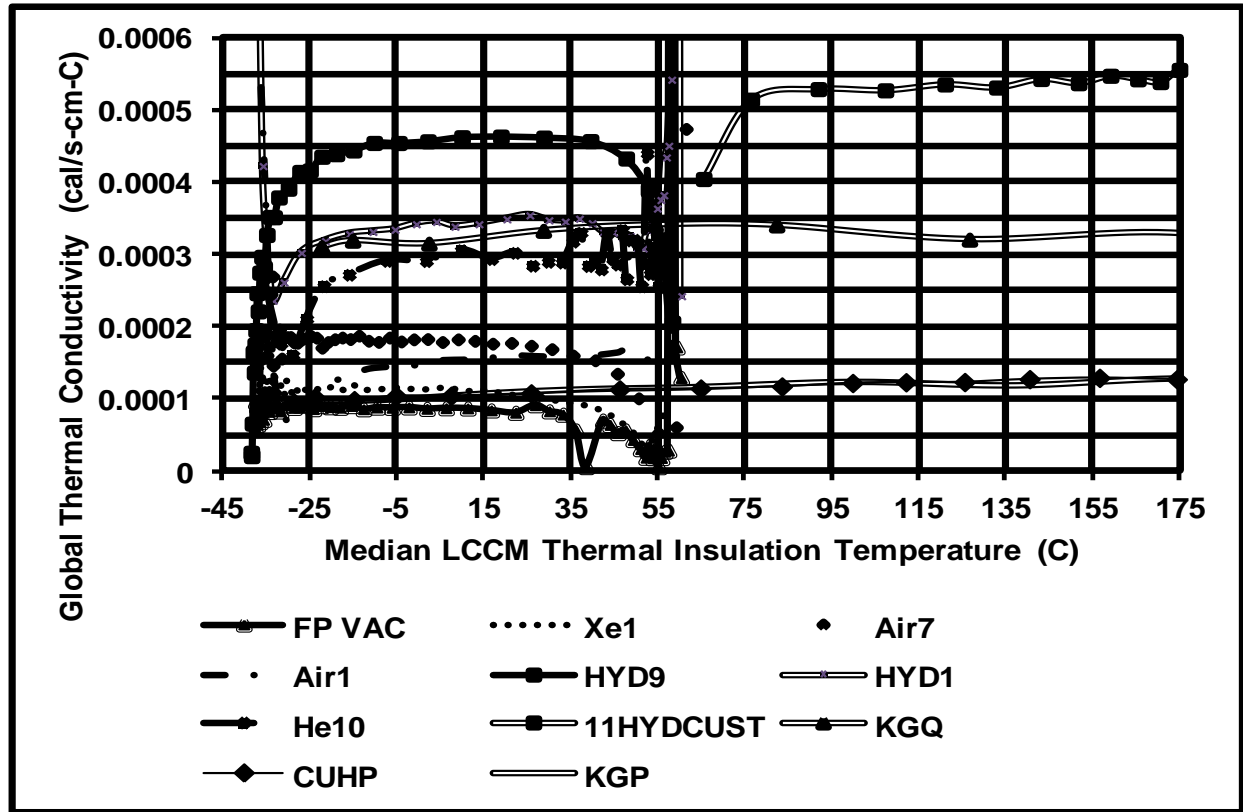


Figure 1. Measured global thermal conductivity values for the LCCM thermal insulation package in selected gas atmospheres. Legend numbers are nominal gas pressures in absolute atmospheres. Three of the four curves that include data above 60 °C are quasi-steady-state data from two operating LCCM thermal batteries and from the copper-heat pellet stack using the LCCM thermal insulation package. For low thermal conductivity gases, heat losses through the solid portions of the thermal insulation package become more significant.

Note: FP VAC = fore pump vacuum (~6.7 Pa), Xe = xenon, HYD = hydrogen, He = helium, 11HYDCUST = copper-heat pellet stack (LCCM simulation) high temperature transient heat transfer experiment at 11 atmospheres pure hydrogen absolute, KGQ = operating LCCM thermal battery GPS9Q, CUHP = operating copper-heat pellet stack (LCCM simulation, quasi-steady-state experiment), KGP = operating LCCM thermal battery GPS9P.

Quasi-steady-state measurements used operating LCCM thermal batteries, as well as a copper-heat pellet stack where copper disks simulated the thermal cell stack, both geometrically and thermally. An LCCM thermal battery (or copper-heat pellet stack) was built into a reusable LCCM case test fixture, insulated with an LCCM thermal insulation package, and fitted with a gas handling system. Type K thermocouples were spot-welded to SS disks in the LCCM cell

stacks and to SS disks placed in the copper-heat pellet stack. A type K thermocouple was packed firmly into a 1/8-in-diameter thermocouple well drilled into the side of the SS reusable LCCM case test fixture using glass electrical tape (Scotch #69) and mica for both types of tests (LCCM and copper-heat pellet stack). The pyrotechnic materials were ignited and the LCCM electrochemical-heat-source voltaic cell stacks then functioned normally while cooling through the thermal insulation package. After heat pellet ignition, the copper-heat pellet stack rose to a maximum temperature of about 500 °C, and then cooled normally through the thermal insulation package. Global LCCM thermal insulation package thermal conductivity values were then measured from the resulting temperature-time curves of the LCCM battery and copper-heat pellet stacks and cases using the known geometric configurations and component heat capacities as described in detail in reference 1.

After the initial quasi-steady-state test of the LCCM battery designated GPS9SU was complete, the transient tests were done by moving the GPS9SU reusable test fixture filled with various gas atmospheres between two Tenney temperature chambers held at -40 and at +60 °C (appendix A). The experimental curves (figure 1) show anomalously high and low thermal conductivity values measured for the transient tests near the temperature boundaries of -40 and +60 °C, as expected. The effects of the gas atmospheres on the global thermal conductivity values for the LCCM thermal battery package can be seen most clearly in the central portion of the heating/cooling curves where transient heating/cooling effects are minimized. Previously reported quasi-steady-state thermal conductivity values of two operating LCCM thermal batteries (KGP and KGQ) and of a copper-heat pellet stack LCCM heat transfer simulation (CUHP) are shown for comparison (1). For the CUHP experiment, the copper-heat pellet stack was heated pyrotechnically to ~500 °C using the heat pellets and then allowed to cool normally through the thermal insulation package in a fore pump vacuum operating atmosphere (1). Thermal conductivity values measured from the KGP cooling curves are almost identical to those measured from the CUHP cooling curves because the thermal insulation package was under a fore pump vacuum for both experiments. The GPS9Q LCCM thermal battery was sealed in dry room air at one atmosphere and then initiated. The GPS9Q thermal conductivity values (KGQ) measured from the cooling curves clearly show significant quantities of hydrogen gas in GPS9Q (1). The maximum GPS9Q gas pressure was nominally 10.7 abs atm (~1.08 MPa). Transient heating/cooling curves and thermal conductivity values for the copper-heat pellet stack experiment are also shown for a transient test done at temperatures above 60 °C in an atmosphere of pure hydrogen gas at 11 atmospheres absolute (11HYDCUST). Figure 2 shows selected data from figure 1 for the LCCM thermal insulation package global thermal conductivities for ultra pure carrier grade hydrogen at 1 and at 9 atmospheres absolute in the central temperature region of the experiment compared with those of air at 1 and at 7 atmospheres absolute.

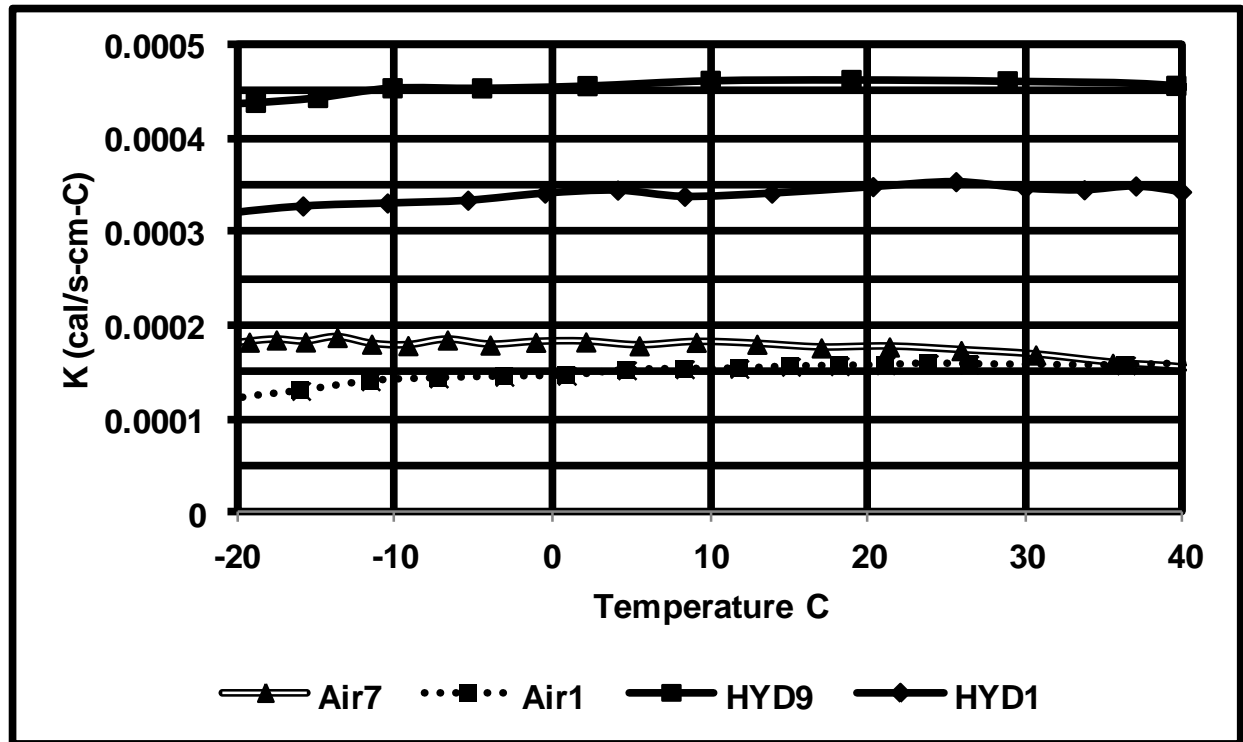


Figure 2. Measured global thermal conductivity values for the LCCM thermal insulation package in air at nominal pressures of 1 and 7 atmospheres absolute and in hydrogen at nominal pressures of 1 and 9 atmospheres absolute.

The data shown in figures 1 and 2 are intended to provide a rapid overview and facilitate an intuitive understanding of the significance of the experimental results. In appendix A, tests using additional gases are shown, and the test results are shown in more easily distinguishable graphical (and tabular) form for increased clarity and precision.

#### 4. Hydrogen Removal by Oxidation with Barium Chromate

Oxidation of hydrogen gas using a mixture of oxidizing heat paper ash (ash from ~21/79 w/o Zr/BaCrO<sub>4</sub> heat powder) and pure BaCrO<sub>4</sub> was previously shown to be a highly effective method of removing hydrogen gas evolved from LCCM flight test heat paper (2). Subsequent experiments showed that BaCrO<sub>4</sub> was much more effective in removing H<sub>2</sub> than was the oxidizing heat paper ash.

The experiments were done in the previously reported (2) modified gas handling system, shown in figure 3. The modified gas handling system used filters and metering valves to prevent large gas flow rates and gross particulate redistribution that had caused failure of the bellows valves in the original gas handling system (2, 5). MV2 was the metering valve that connected the gas handling system with the BaCrO<sub>4</sub> experiments shown in figures 4 and 5. MV2 was closed during



pyrotechnic ignition and when opening BV7. The metering valves were designed to permit a low rate of gas flow when completely closed. The metering valves were all completely open for measurements of the equilibrium gas pressures (maximum pressures and final pressures) that permitted the measurements of the total quantities of gases present in the experiments of figures 4 and 5.

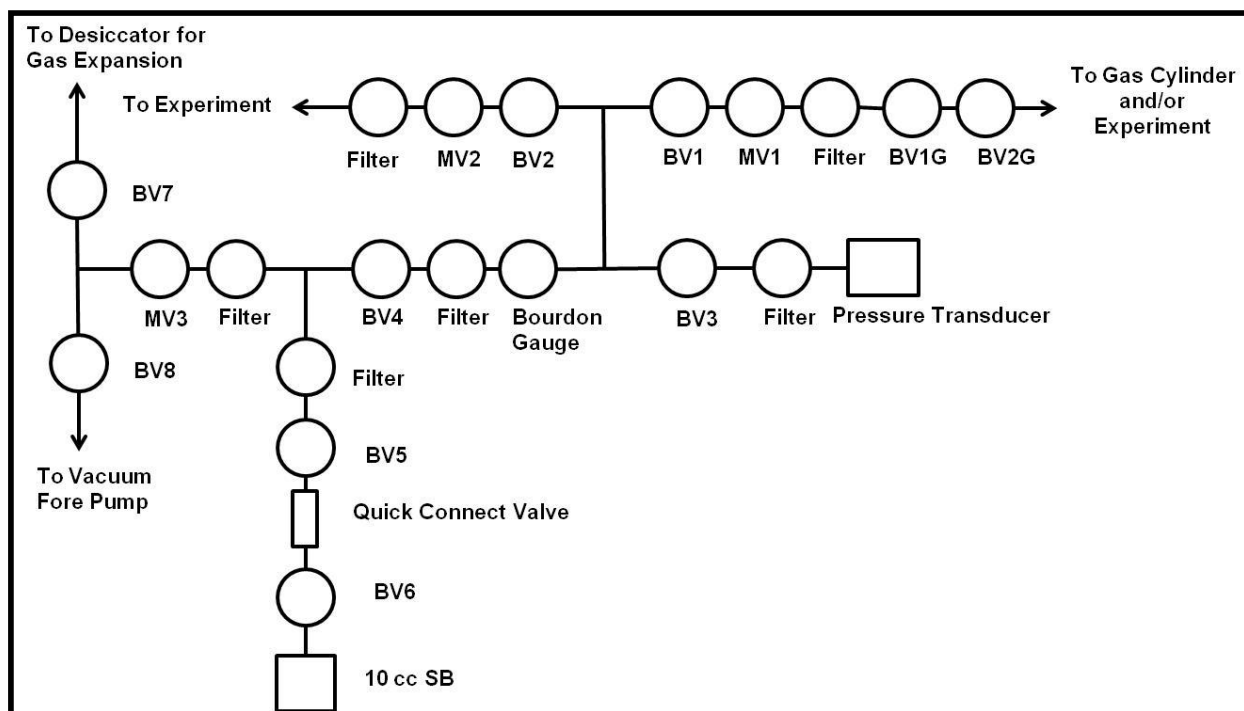


Figure 3. Modified gas handling system. The filters are 0.5  $\mu$ .

Note: BV = bellows valve, MV = metering valve, SB = sample bottle.

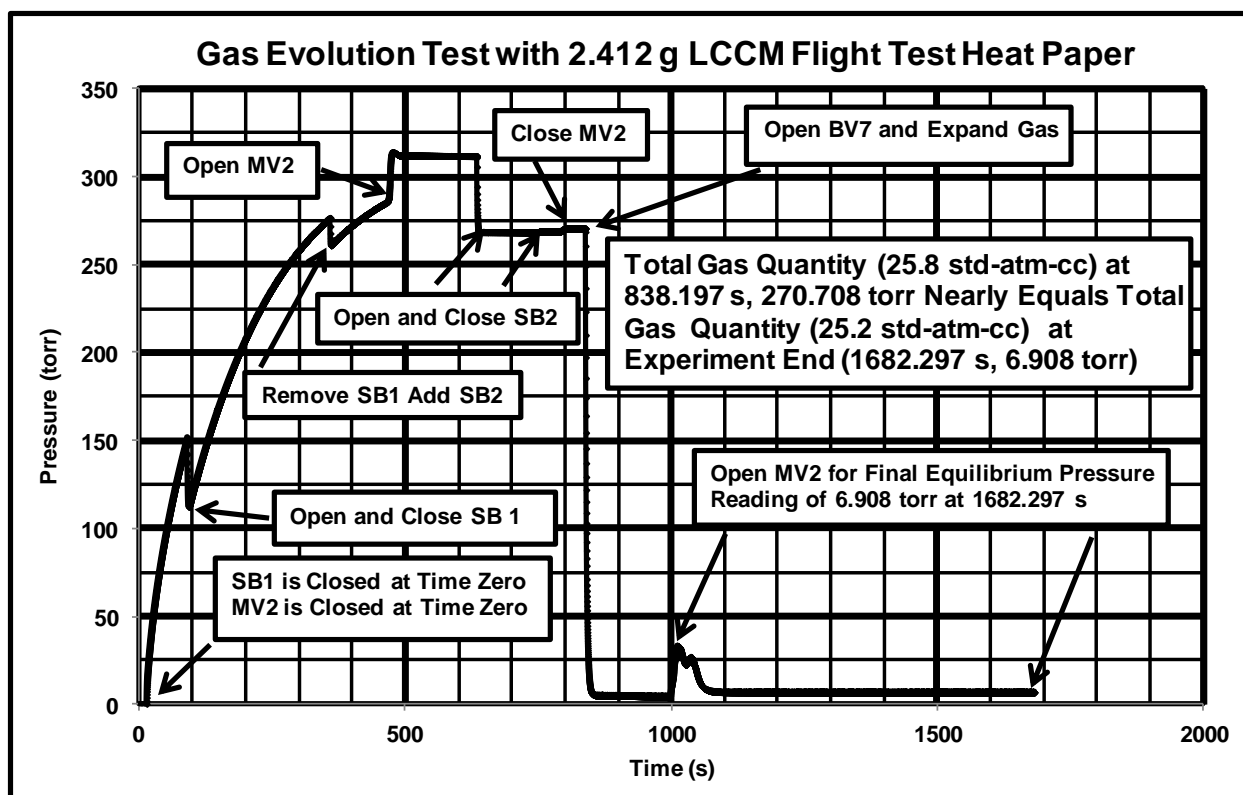


Figure 4. Gas evolution test for LCCM flight test heat paper. The constant pressures at ~314, ~270, and ~6.9 Torr with MV2 open strongly suggest that the ash is not reacting significantly with the gas at those pressures. The nearly equal gas volumes at ~314, ~270, and ~6.9 Torr, combined with the chromatographic analyses, show that little or no water vapor was formed during the experiment.

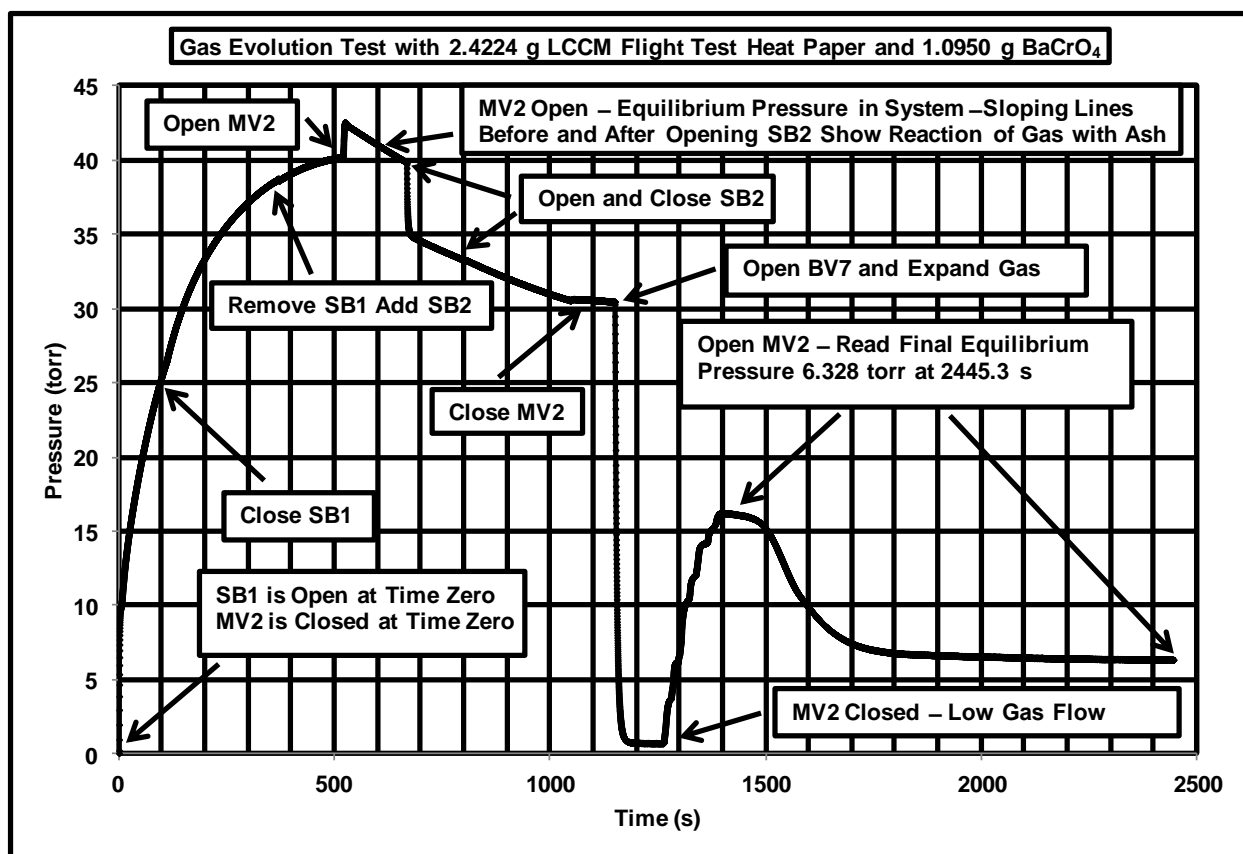


Figure 5. Gas evolution test for LCCM flight test heat paper in physical contact with barium chromate. Pressure decreases starting at ~42 and at ~35 Torr during the test show a reaction of the ash with the gas atmosphere.

LCCM used a common heat paper formulation made from 28/72 w/o Zr/BaCrO<sub>4</sub> heat powder, which forms a reducing ash that favors the formation of H<sub>2</sub> gas (2, 4). Pressure-time curves for tests with LCCM flight test heat paper only and with LCCM flight test heat paper in contact with pure BaCrO<sub>4</sub> are shown in figures 4 and 5.

The initial equilibrium gas pressures (maximum pressures) shown in figures 4 and 5 are produced by nearly identical masses of LCCM heat paper in the same test apparatus. Comparing figures 4 and 5, the initial equilibrium pressure developed by the heat paper gas evolution was therefore reduced from ~314 Torr to ~42 Torr by the oxidizing action of the pyrotechnically heated BaCrO<sub>4</sub>. The gas in the figure 4 experiment contained no significant water vapor. The gas in the figure 5 experiment was saturated with water vapor at ~20 Torr (room temperature pressure of water vapor), so that the maximum equilibrium pressure of the gas that is not water vapor in figure 5 is approximately  $\sim(42-20)=22$  Torr. This indicates an equilibrium pressure (and total gas quantity that is not water vapor) reduction to  $\sim 22 \times 100 / 314 = 7.01\%$  of the quantity of gas that would be present initially in the experiment of figure 5 immediately after opening MV2 if additional BaCrO<sub>4</sub> had not been added. The equilibrium pressures in the LCCM reducing ash test of figure 4 did not increase with time, so the ash did not evolve any significant quantities of

water vapor or other gases after the initial gas formed during ignition, even at the lengthy low pressure plateau near the end of the experiment. The equilibrium pressures in figure 5 were originally much less than those in figure 4, decreased noticeably for all times less than ~1050 s, and were still decreasing slightly at the end of the figure 5 experiment (2445.3 s). Neither test produced ash that increased the system gas pressure after the initial heat paper ignition, which is important, because increased gas pressures increases the global thermal conductivity of the thermal insulation package. The gas types and quantities evolved in the two tests are summarized in table 1 and shown on the basis of more complete analyses in appendix B.

The data in table 1 show that the sample of LCCM flight test heat paper used in the test of figure 4 evolved 10.71 std-atm-cc of gas per gram of heat paper, which was 82.4% hydrogen by volume of the first gas sample collected, and that no significant amount of water vapor was evolved. Assuming that the LCCM flight test heat paper in the figure 5 test in the absence of BaCrO<sub>4</sub> would also have evolved 10.71 std-atm-cc of gas/g of heat paper with the same hydrogen percentage, the hydrogen quantity in the figure 5 test has been reduced from an initial value of  $10.71 \times 0.824 \times 2.4224 = 21.38$  std-atm-cc to  $0.4329 \times 0.780 \times 2.4224 = 0.8180$  std-atm-cc by the end of the test. This amounts to  $0.8180 \times 100 / 21.38 = 3.826\%$  of the original hydrogen value by the end of the experiment. Adding BaCrO<sub>4</sub> to the flight test heat paper therefore removed  $(21.38 - 0.8180) / 1.095 = 18.78$  std-atm-cc H<sub>2</sub>/g of added BaCrO<sub>4</sub> by the end of the experiment (appendix B).

The total amount of gas at the end of the reducing ash experiment was  $10.71 \times 2.412 = 25.83$  std-atm-cc and the total amount of gas at the end of the oxidizing ash experiment including the water vapor was  $2.4224 \times (0.4329 + 7.343) = 18.84$  std-atm-cc. Because one molecule of hydrogen gas is required to form one molecule of water vapor, the fact that these two total gas volumes are not approximately equal suggests that the oxidizing ash removed some water from the system completely. Any liquid water formed by the oxidizing ash in an operating thermal battery will initially form water vapor quantities determined by the temperature of the oxidizing ash.

Table 1. Oxidation of hydrogen gas evolved from LCCM heat paper using BaCrO<sub>4</sub>.

<b>Total Gas Evolved/g of Heat Paper (Excluding Water Vapor) std-atm-cc/g</b>		
	<b>2.412 g Heat Paper</b>	<b>2.4224 g Heat Paper + 1.0950 g BaCrO<sub>4</sub></b>
	<b>10.71</b>	<b>0.4329</b>
<b>SB1 (SB2) Gas Volume Percentages</b>		
H <sub>2</sub>	<b>82.4 (72.7)</b>	<b>78.0 (60.5)</b>
O <sub>2</sub>	<b>0.00 (2.13)</b>	<b>3.03 (6.71)</b>
N <sub>2</sub>	<b>0.00 (0.00)</b>	<b>6.76 (21.3)</b>
CO	<b>16.2 (23.4)</b>	<b>12.3 (11.5)</b>
CH <sub>4</sub>	<b>1.44 (1.81)</b>	<b>0.00 (0.00)</b>
CO <sub>2</sub>	<b>0.00 (0.00)</b>	<b>0.00 (0.00)</b>
<b>Total</b>	<b>100.04 (100.04)</b>	<b>100.09 (100.01)</b>
<b>Apparent Total Water Vapor Volume after Gas Expansion std-atm-cc/g of Heat Paper</b>		
	<b>0.00</b>	<b>7.343 (at 2445.3 s)</b>

## 5. Hydrogen Gas Gettering

Hydrogen gas gettering from atmospheres of pure hydrogen using Zr-based gas getters heated to 300 °C showed high getter reaction rates and capacities. Zr-based gas getters have been used for approximately 50 years and are well characterized for traditional getter applications. However, traditional gas getter applications typically remove gases from devices that are already at low pressures and are then required to hold the resulting significantly lower pressures in electronic devices or vacuum insulators over periods of months or years. A traditional getter might not be required to actually reach the desired low pressure for several days or weeks after the device is sealed. An American Society for Testing and Materials (ASTM) standard test to measure gas gettering rates and capacities for these getters (6) is done in the molecular flow region, at pressures not to exceed  $5 \times 10^{-4}$  Torr ( $6.7 \times 10^{-2}$  Pa). Rapid removal of hydrogen gas at pressures of 1 atm or greater is not ordinarily required. Gas getter vendor representatives were optimistic that this getter could remove hydrogen gas from pressures of ~10 atm down to ~10 Torr or less within seconds but were not aware of any published data that could support their optimism.

The reaction of Zr-based getter materials with hydrogen is reversible and occurs most rapidly at 300 °C. At 300 °C, the Zr-based gas getter tested in this report has removed 136.8 std-atm-cc of

hydrogen gas from a pure hydrogen atmosphere in ~10 s and demonstrated a gross hydrogen removal capacity of 175.1 std-atm-cc of hydrogen/g of getter material (5). At 700 °C, most hydrogen will be reversibly expelled from this gas getter material. Large quantities of hydrogen gas can be removed with this getter material at room temperature or below, but the getter reaction rates will be too slow to prolong most short-life munitions thermal battery lifetimes significantly. Because munitions thermal battery electrochemical cells typically operate at temperatures ranging from 600 to 330 °C and have outer case temperatures typically ranging from –40 to 300 °C during the operating lifetimes, the getter can be placed within the thermal insulation at some point where the temperature will be near 300 °C during normal battery operation for most practical applications.

Gas gettering tests done in pure hydrogen atmospheres are shown in figures 6 through 8. All four tests started with nominally 2 g of getter material at 300 °C under a fore pump vacuum of ~0.05 Torr (6.7 Pa). Measured hydrogen gas quantities ranging from 105.7 to 148.3 std-atm-cc of ultra pure carrier grade hydrogen gas at initial pressures ranging from nominally 7 to 10 atmospheres absolute were stored in the gas handling system and then allowed to enter the evacuated SS tube and react with nominally 2 g of Zr-based gas getter at 300 °C. For the four tests shown in figures 6 and 7, the hydrogen gas pressure would have been reduced to pressures ranging from nominally 3 to 5 atmospheres absolute by simple gas expansion if there had been no hydrogen removal action from the getter. The final atmospheric pressures for the experiments if no hydrogen had been removed, shown on the figures as  $P_o$  values, were calculated using the measured system temperatures with the ideal gas law. These  $P_o$  confirmation measurements implicitly used the 10-cc sample bottle as a volume reference standard for all of the gas handling system component volumes measured as explained in section 2. The  $P_o$  value calculated in this way for the test shown in figure 9 was confirmed experimentally to an accuracy of better than  $\pm 0.1\%$  using a dual capacitance manometer to measure the gas pressure while the tube furnace heated the SS tube at 300 °C using helium as a test gas. The close agreement of calculation and experiment for the  $P_o$  gas pressure of figure 9 is particularly important because the gas quantities removed in that experiment were small. All of the gas gettering tests were done with the metering valves completely open (figure 3). The measured gas pressures for the gettering tests can therefore be used to determine the gas quantities present in real time throughout the course of all of the gas gettering tests.

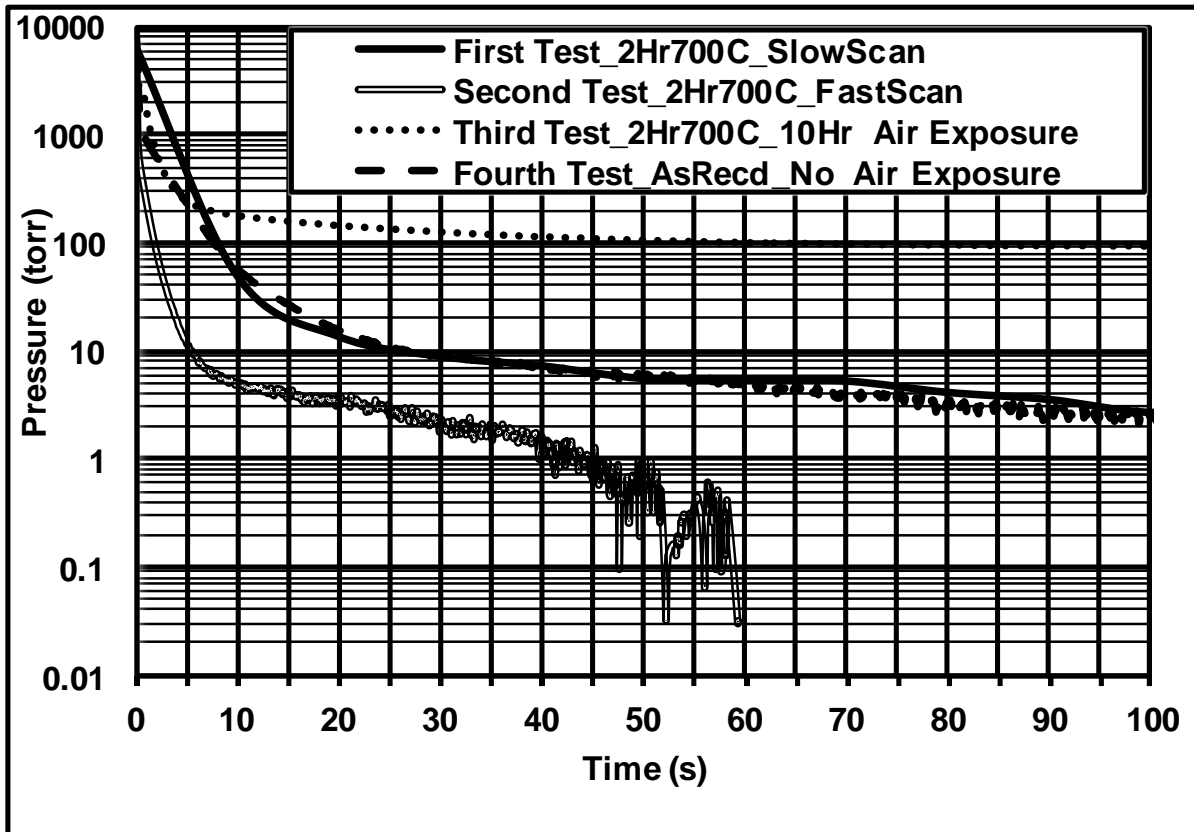


Figure 6. Gas getter tests in pure hydrogen (full pressure range).

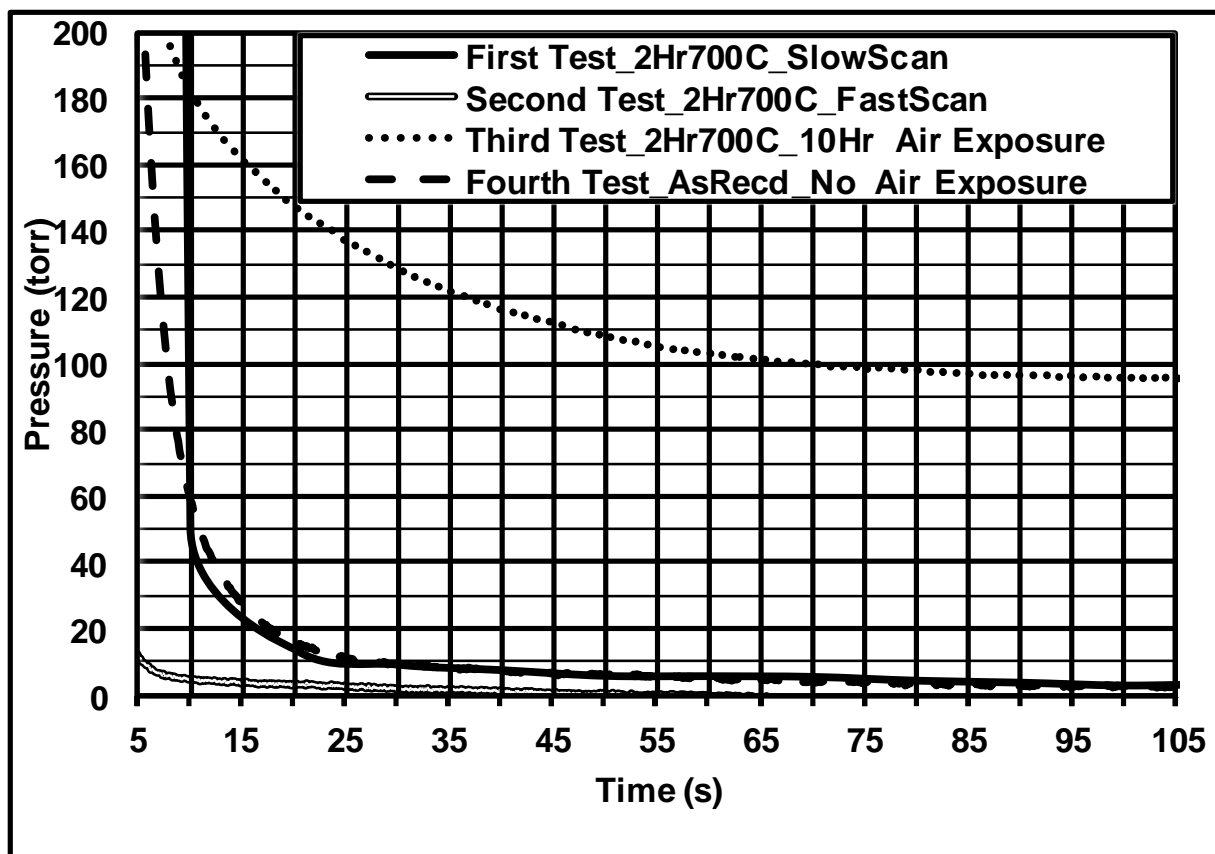


Figure 7. Gas getter tests in pure hydrogen (low pressure range).

The first test used 2.026 g of getter material that had been preheated under Ar for ~2 h at 700 °C and used a slow scan rate (1 reading each 10 s). The scan rate was then increased to 10 readings per second for the three subsequent tests. The second test was a repeat of the first test with the higher scan rate and used 2.082 g of getter. The third test used 1.992 g of getter that had been preheated under helium for ~2 h at 700 °C, cooled to room temperature, and then exposed to dry room air for ~10 h at a dew point of nominally -60 °C. The second and third tests were done to illustrate the effect of exposing the getter to dry room air under normal thermal battery construction conditions. The second and third tests used getter material taken from a larger initial single sample of 4.733 g that was split into two portions in an attempt to increase the initial uniformity of those samples. The fourth test used 2.029 g of getter as received (no 700 °C pretreatment under helium) and had been heated under a helium atmosphere to 300 °C ~2.5 h before the test. Measured gas pressures for all four tests are shown in figures 6 and 7. For the first test, time zero is a rough estimate because of the slow scan rate. For the three tests using a scan rate of 10 readings/s, time zero for the curves below was chosen from the data readouts ~0.1 s before the initial pressure in the gas handling system began to decrease as the hydrogen entered the evacuated SS tube containing the getter material at 300 °C.



Figure 7 is shown with the starting point changed to 5 s after the point of initial pressure decrease and with a reduced pressure range to illustrate more clearly the low gas pressure behavior produced after 5 s of exposure of hydrogen to the getter material. Although tests 2 and 4 appear substantially different in figures 7 and 8 because of the reduced pressure range, both tests removed more than 98.4% of the hydrogen gas originally present by 10 s after the original hydrogen exposure, and more than 99.9% of the hydrogen gas originally present by 60 s after the original hydrogen exposure, as confirmed by calculations for the fourth test shown in appendix C and summarized in figure 8.

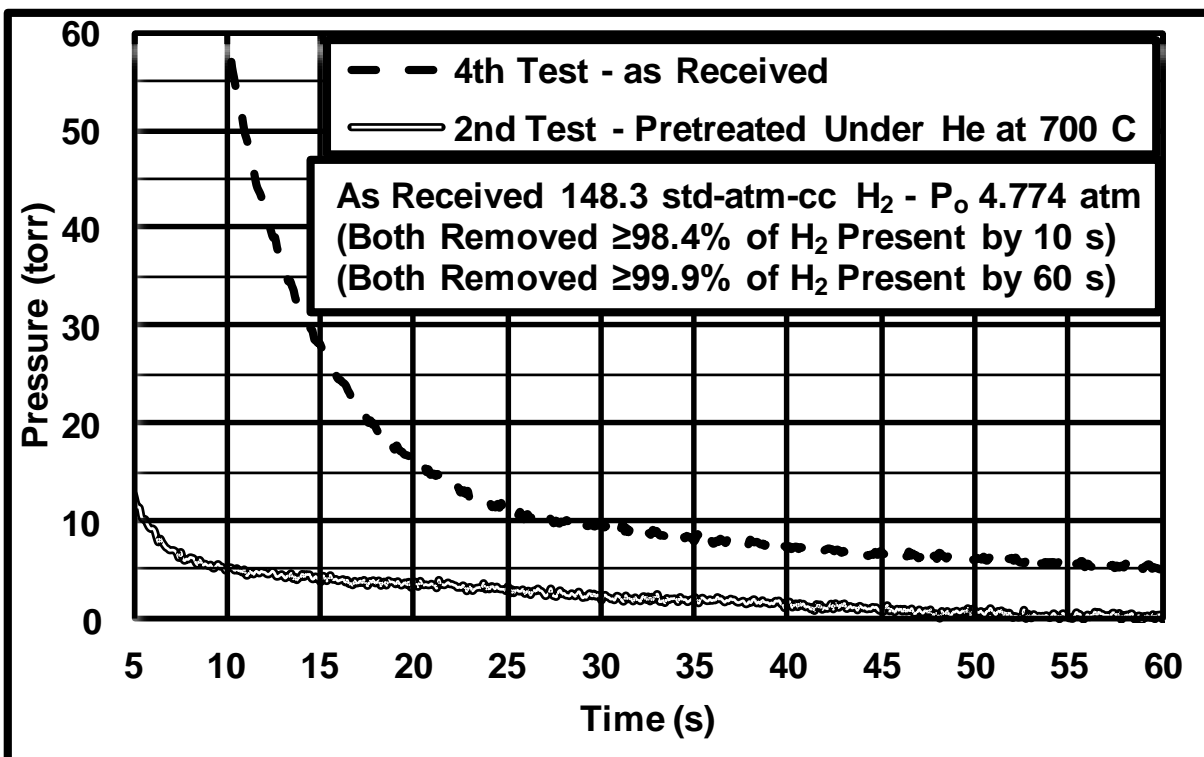


Figure 8. Gas getter tested in pure hydrogen as received and after 700 °C heating under helium (low pressure range).

The third test used getter material that had been exposed to dry room air for 10 h. Although the third test showed a significantly higher gas pressure, that gas getter material still removed 93.5% of the hydrogen (of 115.6 std-atm-cc originally present) by 10 s after the original exposure to hydrogen. That test shows that the getter could be exposed to dry room air using present thermal battery construction methods and still be effective.

Hydrogen gas gettering rates and capacities in hydrogen/air gas mixtures were reduced substantially from the rates in pure hydrogen atmospheres, but were still large enough to be potentially useful (figure 9). Gas chromatographic analyses at the end of the hydrogen/air experiments showed that all of the air had been removed and only hydrogen gas remained. An Excel sheet analysis of a hydrogen/air gas mixture test is shown in appendix C-2. The tests with

hydrogen/air mixtures illustrated the importance of reducing thermal battery gas evolution to very low levels if getter materials are to be used for hydrogen gas reduction.

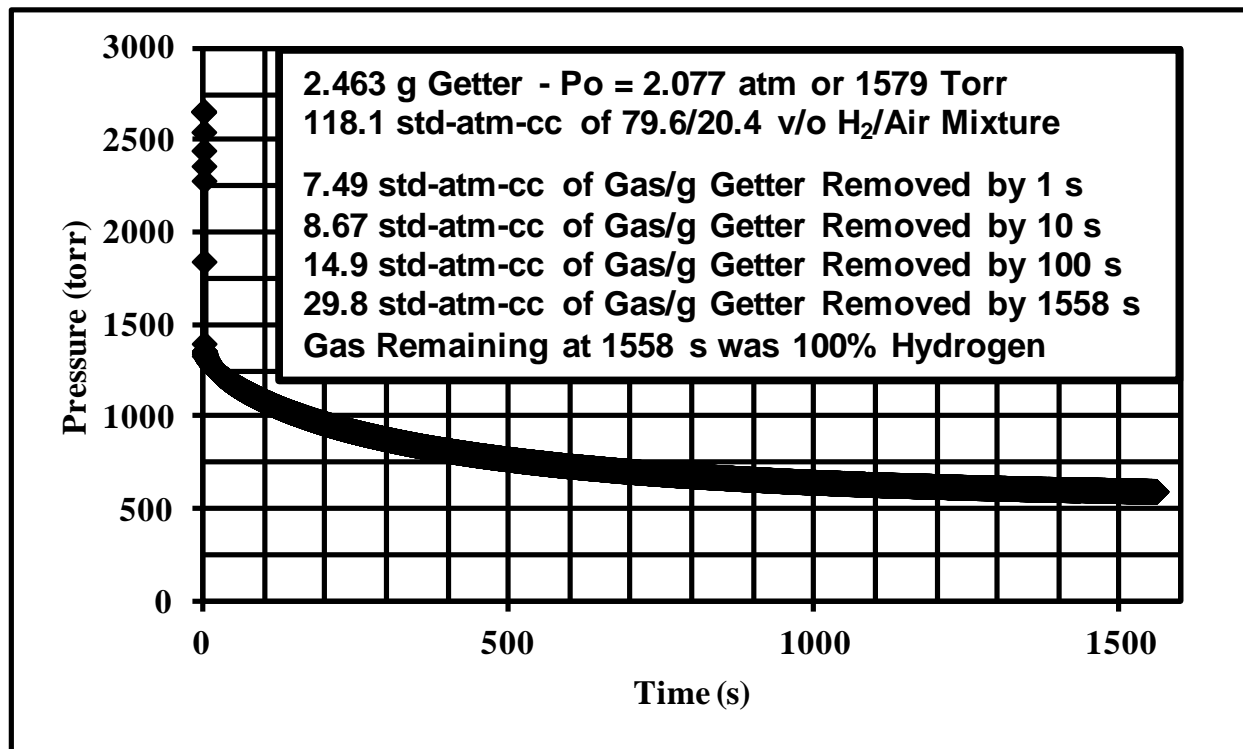


Figure 9. Gas gettering from a 79.6/20.4 volume percent hydrogen/air mixture.

Hydrogen gas gettering rates from  $H_2$ /Xe mixtures are expected to be rapid and will be confirmed in the near future. This is important because the batteries can be backfilled with chemically inert Xe gas during manufacture to reduce or eliminate  $O_2$  and  $N_2$  in the operating gas atmosphere and to reduce the global thermal conductivity of the thermal insulation package.

## 6. Thermal Modeling

The Fortran program used to calculate the global thermal conductivity values of the LCCM thermal insulation package shown in appendix A is an adaptation of a highly effective, thoroughly tested Fortran thermal battery heat transfer optimization program developed at ARL/Adelphi that has been reported previously (1). Most of the heat capacity data used have been reported to be accurate to better than  $\pm 1\%$  (1, 7). Uncertainties in geometric positions and temperature distributions within the battery generally limit the accuracy of the calculated lifetimes to  $\pm 15\%$  in the absence of special effort. Fortran programs, supplemented by Excel spreadsheet analyses, remain a rapid and reliable method of thermal battery heat transfer optimization. Sierra finite element thermal battery heat transfer programs can greatly enhance the

rapid display of arbitrary internal temperature distributions and other operating parameters of the thermal battery electrochemical-heat-source stack and insulation package throughout the operating battery lifetimes.

---

## 7. Summary and Conclusions

---

The effect of hydrogen and other gases on the global thermal conductivity of LCCM thermal insulation packages was confirmed directly using transient heat transfer experiments. Graphical and tabular experimental values for the global thermal conductivity of the LCCM thermal insulation package are reported. The global thermal conductivity of thermal battery thermal insulation packages in controlled gas atmospheres can be measured easily and is a direct demonstration of the effectiveness of hydrogen removal methods.

BaCrO<sub>4</sub> placed in physical contact with LCCM heat paper reduced the hydrogen gas evolution quantity to ~7.01% of its original value early in the figure 5 experiment and to ~3.83% of its original value by the end of the figure 5 experiment. Previous experiments that did not use metering valve restrictions have shown low gas quantities similar to those measured in figure 5 immediately after heat paper ignition. The BaCrO<sub>4</sub> removed a total of 18.78 std-atm-cc of H<sub>2</sub> gas/g of BaCrO<sub>4</sub> by the end of the figure 5 experiment. By using Zr and BaCrO<sub>4</sub> of increased chemical purity in the heat paper, and by adding sufficient BaCrO<sub>4</sub>, it should be possible to essentially eliminate hydrogen gas from operating thermal batteries. Any liquid water formed by this method of hydrogen oxidation will initially be present at the vapor pressure of water at the temperature of the oxidizing heat paper ash. If hydrogen gas could be removed completely from operating thermal battery atmospheres, it should be possible to increase munitions thermal reserve battery energy densities (reduce volumes) by factors ranging from 1.5 to 3. Significantly greater volumetric energy density improvement is possible if the batteries are backfilled with low thermal conductivity chemically inert gases such as Kr or Xe during manufacture. BaCrO<sub>4</sub> has the advantage that it is inexpensive, and that the hydrogen gas oxidizing ash formed is not present at all until the thermal battery pyrotechnic material is initiated, so there is no need to protect an active chemical surface during the required 20-year storage lifetime of the thermal battery. The possible presence and extent of chemical reactions that form hydrogen gas from water in thermal batteries that operate with higher case temperatures than LCCM must be evaluated before using this method of reducing hydrogen gas in the operating battery atmosphere.

Zr-based gas getters are highly effective in atmospheres of pure hydrogen, but were much less effective in mixtures of hydrogen and air. If Zr-based gas getters are to be used in practical applications, the presence of the other gases commonly found in thermal battery operating atmospheres (O<sub>2</sub>, N<sub>2</sub>, CO, CH<sub>4</sub>, and CO<sub>2</sub>) must also be minimized. Backfilling thermal batteries with chemically inert, low thermal conductivity gases such as Xe or Kr during manufacture could eliminate air from the operating atmosphere and improve gas getter performance by reducing the

global thermal conductivity of the thermal insulation package. Battery construction methods, materials selection, chemical processing, internal construction methods, and internal heat balancing can all be effective gas control methods. The use of pyrotechnic iron powders that yield small quantities of hydrogen gas and the choice of thermal insulators with minimal quantities of hydrogen gas evolution from binder materials and tape adhesives could be highly effective. If Zr-based gas getters were used, they would require some method of protecting the active getter surface during the required 20-year thermal battery storage lifetime.

The removal of hydrogen gas from various gas atmospheres is more easily studied independently from thermal battery operation. A number of factors arising from thermal battery operation can easily mask the effectiveness of gas removal techniques if battery electrical output is used as the sole criterion of success of the gas getter. Small internal modifications can produce large differences in the measured thermal lifetimes. A slight increase in the amounts of anodic or cathodic active electrochemical materials, a slight increase or decrease in electrochemical-heat-source cell stack length or diameter, a slight change in an internal local or global heat balance, or a slight change in the types and placement of adhesive tapes and thermal insulation binders can all produce large changes in the measured battery lifetimes for specific applications. This is especially true in munitions thermal batteries such as LCCM, where the thermal capacity of the thermal insulation package is large with respect to the thermal capacity of the electrochemical-heat-source stack. For LCCM, the initial transient heating effects of the thermal insulation can easily mask the effects of lower thermal conductivity of the thermal insulation package. For the effective study of thermal battery improvement using gas control methods, collaboration with a thermal battery vendor is suggested.

Placement of pyrotechnic material such that the insulation package is properly heated without overheating the thermal cells is crucial and the proper placement must be determined experimentally. If the internal pyrotechnic material is placed correctly during thermal battery construction, it should be possible to increase the electrical lifetimes of most presently fielded munitions thermal batteries by values inversely proportional to the reduction of the thermal conductivity values obtained by removing hydrogen gas. This means that the present volumetric energy density of LCCM could be improved by a factor of 3 (1, 2). Many thermal batteries have significantly longer lifetimes than LCCM and the effects of hydrogen gas removal in such batteries could be of proportionately greater significance and could be more easily demonstrated.

---

## 8. References

---

1. Krieger, F.; Ding, M. *Heat Transfer in the LCCM Thermal Reserve Battery*; ARL-TR-4843; U.S. Army Research Laboratory: Adelphi MD, September 2009.
2. Krieger, F. et al. Gas Control Experiments and Calculations for Pressed Pellet Thermal Batteries. *Proc. 45<sup>th</sup> Power Sources Conference*, 551, 2012.
3. Krieger, F. et al. Gas Evolution from Thermal Battery Materials. *Proc. 44<sup>th</sup> Power Sources Conference*, 517, 2010.
4. McIntyre, R. *Procedure for Determination of Gas Evolved by Thermite Mixtures*; TR-702; Diamond Ordnance Fuze Laboratories: Washington D. C., February 1960.
5. Krieger, F.; Lennen R. Practical Miniaturization of the LCCM Thermal Battery using Gas Getters. *Proc. 42nd Power Sources Conference*, 2006, 253.
6. ASTM F 798 – 97 (Reapproved 2002), “Standard Practice for Determining Gettering Rate, Sorption Capacity, and Gas Content of Nonevaporable Getters in the Molecular Flow Region,” ASTM International, West Conshohocken PA (2003).
7. Kelley, K. *Contributions to the Data on Theoretical Metallurgy*; Bureau of Mines Bulletin 584, United States Government Printing Office: Washington, DC, 1960.

INTENTIONALLY LEFT BLANK.

---

## Appendix A. Measured Global Thermal Conductivity Values for the LCCM Thermal Insulation Package

---

This appendix shows thermal modeling methods used for measurement of the global thermal conductivity of the LCCM thermal insulation package in various gas atmospheres. As explained in section 3 of the main report, convection and radiation heat loss rates are not significant. Total heat loss through the insulation package can be calculated using the conduction heat transfer equation  $dq/dt = K \cdot S \cdot \Delta T$  where  $dq/dt$  = heat loss rate (cal/s),  $K$  = thermal conductivity (cal/s-cm-°C),  $S$  = geometric shape factor (cm), and  $\Delta T$  = temperature difference (°C) using the measured  $K$  values (1).

The LCCM thermal battery GPS9SU battery was used for most tests shown in this appendix and had been tested as a fully operating battery in the quasi-steady-state mode before the transient tests were started. The battery contained some sulfur in the insulation package in an unsuccessful attempt to remove hydrogen from the system through hydrogen sulfide formation. Measured thermal conductivity values for GPS9SU by this method agreed with those found for other LCCM thermal batteries and for the copper-heat pellet stack. The added sulfur is not believed to have affected the measured thermal conductivity values.

### A-1. Fortran Input File Used to Calculate Global Thermal Conductivity “K” Values for the LCCM Thermal Insulation Package from Transient Heat Transfer Experiments

Below is the input data file hyd1csi that was used for the measurement of the global thermal conductivity of the thermal insulation package in the LCCM thermal battery GPS9SU when hydrogen is present at nominally one atmosphere in the thermal insulation package.

The experimental heating curve data shown below were obtained by removing the LCCM reusable test fixture containing the fully assembled LCCM thermal battery GPS9SU with attached thermocouples from a temperature chamber at -40 °C and placing it into a temperature chamber at +60 °C. The four columns from left to right are measured values of time (s), cell stack top temperature °C, cell stack bottom temperature °C, and case temperature °C.

0.	-38.659	-38.536	-38.576
29.996	-38.39	-38.135	-37.521
50.014	-37.837	-37.893	-36.006
100.026	-36.956	-37.25	-32.069
150.012	-36.053	-36.525	-28.137
200.015	-34.705	-35.3	-24.307
300.012	-30.711	-31.561	-17.295
400.012	-25.798	-26.816	-10.984
500.023	-20.466	-21.564	-5.207
599.996	-15.184	-16.15	-0.192
700.008	-9.958	-10.883	4.619
800.009	-4.831	-5.741	8.976
900.029	0.03	-0.829	13.054

999.996	4.497	3.658	16.604
1199.996	12.442	11.746	22.681
1400.023	19.119	18.597	27.475
1599.996	24.657	24.186	31.428
1800.025	29.162	28.742	34.955
2000.011	33.032	32.606	38.012
2199.996	36.415	36.022	40.776
2400.	39.324	39.035	43.286
2600.011	41.854	41.679	45.528
2799.996	44.189	44.069	47.58
3000.018	46.263	46.202	49.337
3199.996	48.139	48.12	50.915
3399.996	49.734	49.756	52.244
3600.017	51.159	51.186	53.361
3799.996	52.533	52.479	54.377
4000.017	53.696	53.606	55.194
4199.999	54.699	54.599	55.892
4400.025	55.574	55.432	56.57
4599.996	56.288	56.176	57.104
4799.996	56.972	56.834	57.601
5000.013	57.526	57.386	58.006
5400.009	58.467	58.332	58.735
5800.019	59.137	58.995	59.244
6400.022	59.806	59.651	59.794
6800.005	60.165	60.04	60.085
9409.996	61.007	60.874	60.688

## A-2. Fortran Source File Used to Calculate Global Thermal Conductivity “K” Values for the LCCM Thermal Insulation Package from Transient Heat Transfer Experiments

The text below is the Fortran program su09.for used to calculate the global thermal conductivity “K” values of the LCCM thermal insulation package from the heating curve shown in section A-1. The Fortran program has numerous comment statements for first time users. The Fortran program was written, compiled, and executed in Unix, using a Linux machine, with the help of the ARL “zteam.” Additional program details are available on request.

```

C 1= Fe    6= LiF(s)   11= LiCl(l)   16= Al(l)
C 2= FeO   7= LiF(l)   12= S (rhombic) 17= Heat Pellet
C 3= KCl(s) 8= LiBr(s)  13= Li(s)    18= Anode
C 4= FeS2  9= LiBr(l)  14= Li(l)    19= Elec-Cathode
C 5= MgO   10=LiCl(s)  15= Al(s)    20= Eutectic

C  PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C  PR2= Weight fraction LiF, LiBr, LiCl, Li, Al, in anode.
C  PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
C  electrolyte/cathode.
C  GMW= Gram molecular weights of first 16 substances.
C
C  703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C  453.7 K = 180.55 C = Melting point of Lithium.
C  932 K = 658.85 C = Melting point of Aluminum.
C  70.20 cal/g = Heat of fusion of LiF-LiBr-LiCl eutectic.
C  17.5326 cal/g = Heat of fusion of LiF-LiBr-KBr eutectic in
C  electrolyte-cathode (70.20*(.0238872+.170860+.0550045)
C  = 17.5326).
```



C 7.02 cal/g = Heat of fusion of LiF-LiBr-LiCl eutectic in  
 C anode  $(70.2 * (.00956438 + .0684120 + .0220237) = 7.02)$  (Li(Al)).  
 C The experimental cathode uses 45/55 E/B and anode uses only E.  
 C The separator uses 53/47 E/B. The E/C composition was  
 C calculated using 53/47 E/B for both separators and cathodes.  
 C All heat capacities calculated as sum of component  
 C heat capacities.  
 C Liquid lithium heat capacity used above 453.7 K.  
 C Liquid aluminum heat capacity used above 932 K.  
 C Heat of fusion of lithium  $715/6.94 = 103.026$  c/g is ignored.  
 C Heat of fusion of aluminum  $2570/26.98 = 95.2557$  c/g is ignored.  
 C  $T(K) = T(C) + 273.15$   
 C The sulfur heat capacity used (K. K. Kelley) is for rhombic  
 C sulfur (sulfur at a temperature below 95.45 C)

DOUBLE PRECISION COND

DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(21)

DATA

1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,  
 1 0.,0.,0./,  
 2 PR2/0.,0.,0.,0.,0.,0.00956438,0.,0.0684120,0.,0.0220237,0.,  
 3 0.,0.18,0.,0.72,0./,  
 4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,  
 5 .0550045,0.,0.,0.,0.,0./,  
 6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.85,86.85,  
 7 42.39,42.39,32.07,6.94,6.94,26.98,26.98/

OPEN(UNIT=5,NAME='/home/fkrieger/fk/vk/hyd1csi',TYPE='OLD')

OPEN(UNIT=6,NAME='/home/fkrieger/fk/vk/qfile',TYPE='NEW')

READ(5,111) TI1,TT1,TB1,TCA1

8 READ(5,111,END=219) TI2,TT2,TB2,TCA2

111 FORMAT(F15.8,F15.8,F15.8,F15.8)

IF (((TT2+TB2)/2.).GT.((TT1+TB1)/2.)) THEN

THIGH=(TT2+TB2)/2.

TLOW=(TT1+TB1)/2.

ELSE

THIGH=(TT1+TB1)/2.

TLOW=(TT2+TB2)/2.

END IF

TCASE=0.5\*(TCA1+TCA2)

TIME= TI2-TI1

TM=(THIGH+TLOW)/2.

TIN=(TM+TCASE)/2.

T1=TLOW+273.15

T2=THIGH+273.15

DO I=1,5

IF((T2-T1).EQ.0.) GO TO 19

DELH(I)=ENTG(T1,T2,I)/GMW(I)/(T2-T1)

END DO

DELH(12) = ENTG(T1,T2,12)/GMW(12)/(T2-T1)

IF(T2.LT.703.15) THEN

```

        DELH(6) = ENTG(T1,T2,6)/GMW(6)/(T2-T1)
        DELH(8) = ENTG(T1,T2,8)/GMW(8)/(T2-T1)
        DELH(10)= ENTG(T1,T2,10)/GMW(10)/(T2-T1)
    ELSE IF(T1.GT.703.15) THEN
        DELH(6) = ENTG(T1,T2,7)/GMW(7)/(T2-T1)
        DELH(8) = ENTG(T1,T2,9)/GMW(9)/(T2-T1)
        DELH(10)= ENTG(T1,T2,11)/GMW(11)/(T2-T1)
    ELSE
        DELH(6) = ENTG(T1,703.15,6)/GMW(6)/(T2-T1)
1      + ENTG(703.15,T2,7)/GMW(7)/(T2-T1)
        DELH(8) = ENTG(T1,703.15,8)/GMW(8)/(T2-T1)
1      + ENTG(703.15,T2,9)/GMW(9)/(T2-T1)
        DELH(10)= ENTG(T1,703.15,10)/GMW(10)/(T2-T1)
1      + ENTG(703.15,T2,11)/GMW(11)/(T2-T1)
    END IF
    IF(T2.LT.453.7) THEN
        DELH(13)= ENTG(T1,T2,13)/GMW(13)/(T2-T1)
    ELSE IF(T1.GT.453.7) THEN
        DELH(13)= ENTG(T1,T2,14)/GMW(14)/(T2-T1)
    ELSE
        DELH(13)= ENTG(T1,453.7,13)/GMW(13)/(T2-T1)
1      + ENTG(453.7,T2,14)/GMW(14)/(T2-T1)
    END IF
    IF(T2.LT.932.0) THEN
        DELH(15)= ENTG(T1,T2,15)/GMW(15)/(T2-T1)
    ELSE IF(T1.GT.932.0) THEN
        DELH(15)= ENTG(T1,T2,16)/GMW(16)/(T2-T1)
    ELSE
        DELH(15)= ENTG(T1,932.0,15)/GMW(15)/(T2-T1)
1      + ENTG(932.0,T2,16)/GMW(16)/(T2-T1)
    END IF

    DELH(17)=0.0
    DELH(18)=0.0
    DELH(19)=0.0

    DO J=1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
    END DO

    DELH(20)=.0956438*DELH(6)+.684120*DELH(8)+.220237*DELH(10)

    CPHPAP = 0.14
    CPINS = -.1716+.00009867*(TIN+273.15)
C   Expansion of the battery stack components with temperature.
    XPANST=1.+(TM-22.)*.1118E-4+.53E-8*(TM-22.)**2
    XPANCA=1.+(TCASE-22.)*.1118E-4+.53E-8*(TCASE-22.)**2
    FL1=.8075*2.54*XPANST
    FL2=1.1992*2.54*XPANCA
    D1=0.75*2.54*XPANST
    D2=1.243*2.54*XPANCA
    PI=3.1415927
    RWX=PI*(D1**2/(FL2-FL1)+1.08*D1)
    RWY=PI*2.*FL1/ALOG(D2/D1)
    SHP=RWX+RWY

```

```

XHC = (THIGH-TLOW)*((7.403*DELH(17)
1+2.390*DELH(18))+6.112*DELH(19)+2.759*DELH(1)+
1(CPHPAP*5.055+CPINS*7.426+2.349*DELH(1)
1+0.615*DELH(12))*5)
IF(THIGH.GT.430.1.AND.TLOW.LT.429.9) THEN
TEUTFUS=7.02*2.402+17.5326*5.982
XHC=XHC+TEUTFUS
ELSE
TEUTFUS=0.0
END IF
AVTI= (TI1+TI2)/2.

```

```

COND= XHC/(SHP*TIME*ABS(TCASE-TM))
DELTH= COND*SHP*ABS(TCASE-TM)

```

```

TSTSTHC = 2.759*(T2-T1)*DELH(1)
TINSTHC = 2.349*.5*(T2-T1)*DELH(1)
THPHC = 7.403*(T2-T1)*DELH(17)
TAHC = 2.390*(T2-T1)*DELH(18)
TECHC = 6.112*(T2-T1)*DELH(19)
TPAPHC = 5.055*(T2-T1)*.5*CPHPAP
TINSHC = 7.426*(T2-T1)*.5*CPINS
TSUHC = 0.615*(T2-T1)*DELH(12)

```

```

WRITE(6,220) THIGH,TLOW,DELH(1)
WRITE(6,221) DELH(2),DELH(3),DELH(4)
WRITE(6,222) DELH(5),DELH(13),DELH(15)
WRITE(6,223) DELH(6),DELH(8),DELH(10)
WRITE(6,224) DELH(17),DELH(18),DELH(19)
WRITE(6,225) DELH(20),DELH(12),XHC
WRITE(6,231) CPINS,CPHPAP
WRITE(6,250) TSTSTHC,THPHC,TSUHC
WRITE(6,251) TECHC,TINSHC,TINSTHC
WRITE(6,252) TAHC,TPAPHC
WRITE(6,235) T1,T2,TEUTFUS
WRITE(6,232) COND,TM,TIN
WRITE(6,233) TI1,TI2,TIME
WRITE(6,237) TCA1,TCA2,TCASE
WRITE(6,236) DELTH,AVTI
WRITE(6,242) XHC,XPANST,XPANCA
WRITE(6,243) RWX,RWY,SHP

```

```

19  TI1=TI2
    TT1=TT2
    TB1=TB2
    TCA1=TCA2
    GO TO 8
219 WRITE(6,226)
    WRITE(6,227)
    WRITE(6,228)
    WRITE(6,229)
    WRITE(6,230)
220 FORMAT(' THIGH=',F9.4,' TLOW=',F9.4,' Fe=', F12.7)
221 FORMAT(' FeO=',F12.7,' KCl=',F12.7,' FeS2=', F12.7)

```

```

222 FORMAT(' MgO=',F12.7,' Li=',F12.7,' Al=', F12.7)
223 FORMAT(' LiF=', F12.7,' LiBr=',F12.7,' LiCl=', F12.7)
224 FORMAT(' HPHC=', F12.7,' AHC=',F12.7,' ECHC=', F12.7)
225 FORMAT(' EUT=',F12.7,' SHC=',F12.7,' XHC=',F15.5)
226 FORMAT(' HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2')
227 FORMAT(' ECMASS = 6.112 ANODEMASS = 2.390')
228 FORMAT(' HPELLETMASS = 7.403 STEELSTACKMASS = 2.759')
229 FORMAT(' INSMASS = 7.426 HEAT PAPER MASS = 5.056')
230 FORMAT(' SULFUR MASS = 0.615 MASS STEEL IN INS = 2.349')
231 FORMAT(' CPINS=',F12.7,' CPHPAP=', F12.4)
232 FORMAT(' K=',D18.10,' TAVSTACK=',F8.3,' TAVINS=',F8.3)
233 FORMAT(' TIME1=',F12.5,' TIME2=',F12.5,' INTTIME=',F12.5)
235 FORMAT(' T1=',F12.6,' T2=',F12.6,' TEUTFUS=',F12.6//)
236 FORMAT(' DELTHT=',F12.6,' AVTIME = ',F12.6)
237 FORMAT(' TICASE=',F10.4,' TFCASE=',F10.4,' TCASE=',F10.4)
242 FORMAT(' XHC=',F12.6,' XPANST=',F12.8,' XPANCA=',F12.8)
243 FORMAT(' RWX=',F12.6,' RWY=',F12.6,' SHP=',F12.6//)

250 FORMAT('TSTSTHC=',F12.6,' THPHC=',F12.6,' TSHC=',F12.6)
251 FORMAT('TECHC=',F12.6,' TINSHC=',F12.6,' TINSTHC=',F12.6)
252 FORMAT('TAHC=',F12.6,' TPAPHC=',F12.6)

```

```

999 CONTINUE
    END

```

```

    FUNCTION ENTG(T1,T2,J)

```

```

C   This function calculates the molar heat content between T1 and T2.
C   TR1, TR2, TR3 are molar heat capacity coefficients of the first
C   16 substances.

```

```

    DIMENSION TR1(16),TR2(16),TR3(16)
    DATA
2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
3   16.00, 11.00, 16.00, 3.58, 1.64, 6.78, 4.94, 7.00/,
4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
5   0.00302, 0., .0034, 0., .00624, .0111, 0., .00296, 0./,
6 TR3/ 60000., -67000., 77000., -305000., -148000., -138000., 0.,
7   0., 0., 0., 0., 84000., 99000., 0., 0./
    ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1/T2-1/T1)*TR3(J)
    RETURN
    END

```

### A-3. Fortran Output File – Global Thermal Conductivity “K” Values for the LCCM Thermal Insulation Package Calculated from Transient Heat Transfer Experiments

The text below is the output file hyd1cso from the source program su09.for using the input file hyd1csi. Both heating and cooling curves may be used with the Fortran program. The thermal conductivity “K” is the global thermal conductivity of the thermal insulation package in cal/s–cm–°C and is always calculated as a positive value. More significant figures are included than are experimentally justifiable to facilitate debugging of the Fortran source program. Data shown in addition to the “K” values can be used to facilitate additional calculations using other mathematical models.

THIGH= -38.2625 TLOW= -38.5975 Fe= 0.1057873  
FeO= 0.1584169 KCl= 0.1677595 FeS2= 0.1054665  
MgO= 0.1959849 Li= 0.8314196 Al= 0.2088500  
LiF= 0.3400390 LiBr= 0.1405740 LiCl= 0.2783215  
HPHC= 0.1278725 AHC= 0.3190264 EHC= 0.1466282  
EUT= 0.1899888 SHC= 0.1573013 XHC= 1.38921  
CPINS= 0.1947786 CPHPAP= 0.1400  
TSTSTHC= 0.097777 THPHC= 0.317131 TSHC= 0.032409  
TEHC= 0.300230 TINSHC= 0.242281 TINSTHC= 0.041624  
TAHC= 0.255434 TPAPHC= 0.118542  
T1= 234.552490 T2= 234.887497 TEUTFUS= 0.000000

K= 0.2797025489E-02 TAVSTACK= -38.430 TAVINS= -38.239  
TIME1= 0.00000 TIME2= 29.99600 INTTIME= 29.99600  
TICASE= -38.5760 TFCASE= -37.5210 TCASE= -38.0485  
DELTH= 0.046313 AVTIME = 14.998000  
XHC= 1.389208 XPANST= 0.99934375 XPANCA= 0.99934781  
RWX= 17.910761 RWY= 25.491518 SHP= 43.402279

THIGH= -37.8650 TLOW= -38.2625 Fe= 0.1057761  
FeO= 0.1584829 KCl= 0.1677264 FeS2= 0.1056151  
MgO= 0.1962095 Li= 0.8313189 Al= 0.2088903  
LiF= 0.3403969 LiBr= 0.1405868 LiCl= 0.2783510  
HPHC= 0.1278840 AHC= 0.3190422 EHC= 0.1467668  
EUT= 0.1900383 SHC= 0.1573728 XHC= 1.64885  
CPINS= 0.1948601 CPHPAP= 0.1400  
TSTSTHC= 0.116002 THPHC= 0.376315 TSHC= 0.038471  
TEHC= 0.356565 TINSHC= 0.287591 TINSTHC= 0.049382  
TAHC= 0.303092 TPAPHC= 0.140652  
T1= 234.887497 T2= 235.284988 TEUTFUS= 0.000000

K= 0.1459579216E-02 TAVSTACK= -38.064 TAVINS= -37.414  
TIME1= 29.99600 TIME2= 50.01400 INTTIME= 20.01800  
TICASE= -37.5210 TFCASE= -36.0060 TCASE= -36.7635  
DELTH= 0.082368 AVTIME = 40.005001  
XHC= 1.648851 XPANST= 0.99934763 XPANCA= 0.99936134  
RWX= 17.910492 RWY= 25.491129 SHP= 43.401619

THIGH= -37.1030 TLOW= -37.8650 Fe= 0.1057599  
FeO= 0.1585851 KCl= 0.1676759 FeS2= 0.1058447  
MgO= 0.1965568 Li= 0.8311779 Al= 0.2089535  
LiF= 0.3409509 LiBr= 0.1406069 LiCl= 0.2783972  
HPHC= 0.1279025 AHC= 0.3190701 EHC= 0.1469811  
EUT= 0.1901152 SHC= 0.1574850 XHC= 3.16245  
CPINS= 0.1950232 CPHPAP= 0.1400  
TSTSTHC= 0.222348 THPHC= 0.721517 TSHC= 0.073803  
TEHC= 0.684549 TINSHC= 0.551787 TINSTHC= 0.094653  
TAHC= 0.581091 TPAPHC= 0.269637  
T1= 235.284988 T2= 236.046997 TEUTFUS= 0.000000

K= 0.4227481259E-03 TAVSTACK= -37.484 TAVINS= -35.761  
TIME1= 50.01400 TIME2= 100.02600 INTTIME= 50.01200

TICASE= -36.0060 TFCASE= -32.0690 TCASE= -34.0375  
DELTH= 0.063234 AVTIME = 75.020004  
XHC= 3.162451 XPANST= 0.99935377 XPANCA= 0.99939013  
RWX= 17.909811 RWY= 25.490143 SHP= 43.399956

THIGH= -36.2890 TLOW= -37.1030 Fe= 0.1057380  
FeO= 0.1587250 KCl= 0.1676068 FeS2= 0.1061591  
MgO= 0.1970323 Li= 0.8309860 Al= 0.2090402  
LiF= 0.3417094 LiBr= 0.1406343 LiCl= 0.2784606  
HPHC= 0.1279280 AHC= 0.3191085 EHC= 0.1472745  
EUT= 0.1902205 SHC= 0.1576387 XHC= 3.38061  
CPINS= 0.1952562 CPHPAP= 0.1400  
TSTSTHC= 0.237468 THPHC= 0.770895 TSHC= 0.078915  
TEHC= 0.732711 TINSHC= 0.590135 TINSTHC= 0.101089  
TAHC= 0.620809 TPAPHC= 0.288032  
T1= 236.046997 T2= 236.860992 TEUTFUS= 0.000000

K= 0.2363742533E-03 TAVSTACK= -36.696 TAVINS= -33.399  
TIME1= 100.02600 TIME2= 150.01199 INTTIME= 49.98599  
TICASE= -32.0690 TFCASE= -28.1370 TCASE= -30.1030  
DELTH= 0.067631 AVTIME = 125.018997  
XHC= 3.380614 XPANST= 0.99936199 XPANCA= 0.99943185  
RWX= 17.908779 RWY= 25.488657 SHP= 43.397438

THIGH= -35.0025 TLOW= -36.2890 Fe= 0.1057111  
FeO= 0.1589088 KCl= 0.1675172 FeS2= 0.1065714  
MgO= 0.1976563 Li= 0.8307571 Al= 0.2091554  
LiF= 0.3427059 LiBr= 0.1406709 LiCl= 0.2785448  
HPHC= 0.1279628 AHC= 0.3191641 EHC= 0.1476596  
EUT= 0.1903593 SHC= 0.1578430 XHC= 5.34759  
CPINS= 0.1954995 CPHPAP= 0.1400  
TSTSTHC= 0.375216 THPHC= 1.218711 TSHC= 0.124885  
TEHC= 1.161059 TINSHC= 0.933856 TINSTHC= 0.159729  
TAHC= 0.981344 TPAPHC= 0.455228  
T1= 236.860992 T2= 238.147491 TEUTFUS= 0.000000

K= 0.2615139820E-03 TAVSTACK= -35.646 TAVINS= -30.934  
TIME1= 150.01199 TIME2= 200.01500 INTTIME= 50.00301  
TICASE= -28.1370 TFCASE= -24.3070 TCASE= -26.2220  
DELTH= 0.106945 AVTIME = 175.013489  
XHC= 5.347587 XPANST= 0.99937308 XPANCA= 0.99947321  
RWX= 17.907919 RWY= 25.487413 SHP= 43.395332

THIGH= -31.1360 TLOW= -35.0025 Fe= 0.1056553  
FeO= 0.1593508 KCl= 0.1673071 FeS2= 0.1075595  
MgO= 0.1991532 Li= 0.8303093 Al= 0.2094381  
LiF= 0.3451017 LiBr= 0.1407605 LiCl= 0.2787515  
HPHC= 0.1280521 AHC= 0.3193206 EHC= 0.1485837  
EUT= 0.1906953 SHC= 0.1583444 XHC= 16.10312  
CPINS= 0.1958940 CPHPAP= 0.1400  
TSTSTHC= 1.127097 THPHC= 3.665325 TSHC= 0.376527  
TEHC= 3.511338 TINSHC= 2.812317 TINSTHC= 0.479802

TAHC= 2.950822 TPAPHC= 1.368161  
T1= 238.147491 T2= 242.013992 TEUTFUS= 0.000000

K= 0.3024905454E-03 TAVSTACK= -33.069 TAVINS= -26.935  
TIME1= 200.01500 TIME2= 300.01199 INTTIME= 99.99699  
TICASE= -24.3070 TFCASE= -17.2950 TCASE= -20.8010  
DELTH= 0.161036 AVTIME = 250.013489  
XHC= 16.103125 XPANST= 0.99940044 XPANCA= 0.99953121  
RWX= 17.907333 RWY= 25.486565 SHP= 43.393898

THIGH= -26.3070 TLOW= -31.1360 Fe= 0.1055887  
FeO= 0.1600714 KCl= 0.1669790 FeS2= 0.1091611  
MgO= 0.2015844 Li= 0.8298644 Al= 0.2099151  
LiF= 0.3490070 LiBr= 0.1409116 LiCl= 0.2791002  
HPHC= 0.1282135 AHC= 0.3196394 EHC= 0.1500853  
EUT= 0.1912490 SHC= 0.1591903 XHC= 20.17523  
CPINS= 0.1964372 CPHPAP= 0.1400  
TSTSTHC= 1.406779 THPHC= 4.583509 TSHC= 0.472768  
TECHC= 4.429739 TINSHC= 3.522130 TINSTHC= 0.598862  
TAHC= 3.689053 TPAPHC= 1.708740  
T1= 242.013992 T2= 246.842987 TEUTFUS= 0.000000

K= 0.3188412229E-03 TAVSTACK= -28.722 TAVINS= -21.431  
TIME1= 300.01199 TIME2= 400.01199 INTTIME= 100.00000  
TICASE= -17.2950 TFCASE= -10.9840 TCASE= -14.1395  
DELTH= 0.201752 AVTIME = 350.011993  
XHC= 20.175228 XPANST= 0.99944657 XPANCA= 0.99960285  
RWX= 17.907267 RWY= 25.486454 SHP= 43.393723

THIGH= -21.0150 TLOW= -26.3070 Fe= 0.1055536  
FeO= 0.1608718 KCl= 0.1666380 FeS2= 0.1109249  
MgO= 0.2042692 Li= 0.8298254 Al= 0.2104702  
LiF= 0.3533425 LiBr= 0.1410876 LiCl= 0.2795061  
HPHC= 0.1284180 AHC= 0.3200945 EHC= 0.1517447  
EUT= 0.1918735 SHC= 0.1601750 XHC= 22.18868  
CPINS= 0.1969850 CPHPAP= 0.1400  
TSTSTHC= 1.541151 THPHC= 5.030996 TSHC= 0.521303  
TECHC= 4.908144 TINSHC= 3.870602 TINSTHC= 0.656065  
TAHC= 4.048523 TPAPHC= 1.872577  
T1= 246.842987 T2= 252.134995 TEUTFUS= 0.000000

K= 0.3284581762E-03 TAVSTACK= -23.661 TAVINS= -15.878  
TIME1= 400.01199 TIME2= 500.02301 INTTIME= 100.01102  
TICASE= -10.9840 TFCASE= -5.2070 TCASE= -8.0955  
DELTH= 0.221862 AVTIME = 450.017517  
XHC= 22.188679 XPANST= 0.99950051 XPANCA= 0.99966836  
RWX= 17.907827 RWY= 25.487249 SHP= 43.395077

THIGH= -15.6670 TLOW= -21.0150 Fe= 0.1055625  
FeO= 0.1616720 KCl= 0.1663235 FeS2= 0.1126712  
MgO= 0.2069359 Li= 0.8302990 Al= 0.2110540

LiF= 0.3576746 LiBr= 0.1412726 LiCl= 0.2799328  
HPHC= 0.1286508 AHC= 0.3206635 EHC= 0.1533943  
EUT= 0.1925083 SHC= 0.1612102 XHC= 22.50628  
CPINS= 0.1975137 CPHPAP= 0.1400  
TSTSTHC= 1.557590 THPHC= 5.093450 TSHC= 0.530224  
TEHC= 5.014003 TINSHC= 3.922059 TINSTHC= 0.663063  
TAHC= 4.098637 TPAPHC= 1.892392  
T1= 252.134995 T2= 257.483002 TEUTFUS= 0.000000

K= 0.3316490911E-03 TAVSTACK= -18.341 TAVINS= -10.520  
TIME1= 500.02301 TIME2= 599.99597 INTTIME= 99.97296  
TICASE= -5.2070 TFCASE= -0.1920 TCASE= -2.6995  
DELTH= 0.225124 AVTIME = 550.009521  
XHC= 22.506275 XPANST= 0.99955761 XPANCA= 0.99972707  
RWX= 17.908794 RWY= 25.488623 SHP= 43.397415

THIGH= -10.4205 TLOW= -15.6670 Fe= 0.1056141  
FeO= 0.1624299 KCl= 0.1660514 FeS2= 0.1143084  
MgO= 0.2094444 Li= 0.8312530 Al= 0.2116351  
LiF= 0.3617753 LiBr= 0.1414568 LiCl= 0.2803577  
HPHC= 0.1288992 AHC= 0.3213148 EHC= 0.1549474  
EUT= 0.1931201 SHC= 0.1622408 XHC= 22.15929  
CPINS= 0.1980174 CPHPAP= 0.1400  
TSTSTHC= 1.528771 THPHC= 5.006417 TSHC= 0.523485  
TEHC= 4.968630 TINSHC= 3.857422 TINSTHC= 0.650794  
TAHC= 4.029003 TPAPHC= 1.856471  
T1= 257.483002 T2= 262.729492 TEUTFUS= 0.000000

K= 0.3346076701E-03 TAVSTACK= -13.044 TAVINS= -5.415  
TIME1= 599.99597 TIME2= 700.00800 INTTIME= 100.01202  
TICASE= -0.1920 TFCASE= 4.6190 TCASE= 2.2135  
DELTH= 0.221566 AVTIME = 650.001953  
XHC= 22.159290 XPANST= 0.99961472 XPANCA= 0.99978089  
RWX= 17.909933 RWY= 25.490244 SHP= 43.400177

THIGH= -5.2860 TLOW= -10.4205 Fe= 0.1057030  
FeO= 0.1631378 KCl= 0.1658217 FeS2= 0.1158219  
MgO= 0.2117714 Li= 0.8326204 Al= 0.2122045  
LiF= 0.3656035 LiBr= 0.1416373 LiCl= 0.2807740  
HPHC= 0.1291577 AHC= 0.3220291 EHC= 0.1563895  
EUT= 0.1937014 SHC= 0.1632508 XHC= 21.76267  
CPINS= 0.1984996 CPHPAP= 0.1400  
TSTSTHC= 1.497396 THPHC= 4.909368 TSHC= 0.515499  
TEHC= 4.907815 TINSHC= 3.784269 TINSTHC= 0.637438  
TAHC= 3.951759 TPAPHC= 1.816840  
T1= 262.729492 T2= 267.863983 TEUTFUS= 0.000000

K= 0.3422372101E-03 TAVSTACK= -7.853 TAVINS= -0.528  
TIME1= 700.00800 TIME2= 800.00897 INTTIME= 100.00098  
TICASE= 4.6190 TFCASE= 8.9760 TCASE= 6.7975  
DELTH= 0.217625 AVTIME = 750.008484  
XHC= 21.762672 XPANST= 0.99967092 XPANCA= 0.99983126



RWX= 17.911144 RWY= 25.491972 SHP= 43.403114

THIGH= -0.3995 TLOW= -5.2860 Fe= 0.1058222  
FeO= 0.1637910 KCl= 0.1656320 FeS2= 0.1172042  
MgO= 0.2139039 Li= 0.8343146 Al= 0.2127542  
LiF= 0.3691342 LiBr= 0.1418115 LiCl= 0.2811759  
HPHC= 0.1294202 AHC= 0.3227844 EHC= 0.1577122  
EUT= 0.1942468 SHC= 0.1642256 XHC= 20.78135  
CPINS= 0.1989549 CPHPAP= 0.1400  
TSTSTHC= 1.426680 THPHC= 4.681750 TSHC= 0.493531  
TEHC= 4.710282 TINSHC= 3.609757 TINSTHC= 0.607334  
TAHC= 3.769717 TPAPHC= 1.729090  
T1= 267.863983 T2= 272.750488 TEUTFUS= 0.000000

K= 0.3454162215E-03 TAVSTACK= -2.843 TAVINS= 4.086  
TIME1= 800.00897 TIME2= 900.02899 INTTIME= 100.02002  
TICASE= 8.9760 TFCASE= 13.0540 TCASE= 11.0150  
DELTH= 0.207772 AVTIME= 850.018982  
XHC= 20.781355 XPANST= 0.99972552 XPANCA= 0.99987787  
RWX= 17.912405 RWY= 25.493769 SHP= 43.406174

THIGH= 4.0775 TLOW= -0.3995 Fe= 0.1059610  
FeO= 0.1643766 KCl= 0.1654812 FeS2= 0.1184309  
MgO= 0.2158029 Li= 0.8362083 Al= 0.2132679  
LiF= 0.3722977 LiBr= 0.1419743 LiCl= 0.2815514  
HPHC= 0.1296763 AHC= 0.3235447 EHC= 0.1588911  
EUT= 0.1947435 SHC= 0.1651367 XHC= 19.09938  
CPINS= 0.1993740 CPHPAP= 0.1400  
TSTSTHC= 1.308841 THPHC= 4.297910 TSHC= 0.454682  
TEHC= 4.347825 TINSHC= 3.314229 TINSTHC= 0.557171  
TAHC= 3.461954 TPAPHC= 1.584194  
T1= 272.750488 T2= 277.227509 TEUTFUS= 0.000000

K= 0.3388223995E-03 TAVSTACK= 1.839 TAVINS= 8.334  
TIME1= 900.02899 TIME2= 999.99597 INTTIME= 99.96698  
TICASE= 13.0540 TFCASE= 16.6040 TCASE= 14.8290  
DELTH= 0.191057 AVTIME= 950.012451  
XHC= 19.099379 XPANST= 0.99977672 XPANCA= 0.99992013  
RWX= 17.913633 RWY= 25.495527 SHP= 43.409161

THIGH= 12.0940 TLOW= 4.0775 Fe= 0.1061865  
FeO= 0.1651212 KCl= 0.1653186 FeS2= 0.1199720  
MgO= 0.2181986 Li= 0.8391882 Al= 0.2139532  
LiF= 0.3763182 LiBr= 0.1421915 LiCl= 0.2820524  
HPHC= 0.1300336 AHC= 0.3246389 EHC= 0.1603799  
EUT= 0.1953869 SHC= 0.1663520 XHC= 34.34074  
CPINS= 0.1999197 CPHPAP= 0.1400  
TSTSTHC= 2.348577 THPHC= 7.716972 TSHC= 0.820138  
TEHC= 7.858089 TINSHC= 5.950647 TINSTHC= 0.999784  
TAHC= 6.219882 TPAPHC= 2.836631  
T1= 277.227509 T2= 285.243988 TEUTFUS= 0.000000

K= 0.3422312730E-03 TAVSTACK= 8.086 TAVINS= 13.864  
TIME1= 999.99597 TIME2= 1199.99597 INTTIME= 200.00000  
TICASE= 16.6040 TFCASE= 22.6810 TCASE= 19.6425  
DELTH= 0.171704 AVTIME = 1099.995972  
XHC= 34.340736 XPANST= 0.99984545 XPANCA= 0.99997365  
RWX= 17.915398 RWY= 25.498045 SHP= 43.413445

THIGH= 18.8580 TLOW= 12.0940 Fe= 0.1065019  
FeO= 0.1659583 KCl= 0.1651730 FeS2= 0.1216806  
MgO= 0.2208671 Li= 0.8432612 Al= 0.2147640  
LiF= 0.3808346 LiBr= 0.1424485 LiCl= 0.2826452  
HPHC= 0.1304753 AHC= 0.3260296 EHC= 0.1620403  
EUT= 0.1961253 SHC= 0.1677901 XHC= 29.11585  
CPINS= 0.2005524 CPHPAP= 0.1400  
TSTSTHC= 1.987527 THPHC= 6.533413 TSHC= 0.697984  
TEHC= 6.699008 TINSHC= 5.036827 TINSTHC= 0.846086  
TAHC= 5.270588 TPAPHC= 2.393444  
T1= 285.243988 T2= 292.007996 TEUTFUS= 0.000000

K= 0.3491414827E-03 TAVSTACK= 15.476 TAVINS= 20.277  
TIME1= 1199.99597 TIME2= 1400.02295 INTTIME= 200.02698  
TICASE= 22.6810 TFCASE= 27.4750 TCASE= 25.0780  
DELTH= 0.145560 AVTIME = 1300.009521  
XHC= 29.115850 XPANST= 0.99992728 XPANCA= 1.00003445  
RWX= 17.917603 RWY= 25.501194 SHP= 43.418797

THIGH= 24.4215 TLOW= 18.8580 Fe= 0.1068040  
FeO= 0.1666210 KCl= 0.1650892 FeS2= 0.1230128  
MgO= 0.2229588 Li= 0.8470985 Al= 0.2154402  
LiF= 0.3844073 LiBr= 0.1426628 LiCl= 0.2831395  
HPHC= 0.1308589 AHC= 0.3272669 EHC= 0.1633435  
EUT= 0.1967224 SHC= 0.1689893 XHC= 24.04424  
CPINS= 0.2010723 CPHPAP= 0.1400  
TSTSTHC= 1.639411 THPHC= 5.389639 TSHC= 0.578206  
TEHC= 5.554359 TINSHC= 4.153611 TINSTHC= 0.697894  
TAHC= 4.351597 TPAPHC= 1.968647  
T1= 292.007996 T2= 297.571503 TEUTFUS= 0.000000

K= 0.3544598585E-03 TAVSTACK= 21.640 TAVINS= 25.546  
TIME1= 1400.02295 TIME2= 1599.99597 INTTIME= 199.97302  
TICASE= 27.4750 TFCASE= 31.4280 TCASE= 29.4515  
DELTH= 0.120237 AVTIME = 1500.009521  
XHC= 24.044237 XPANST= 0.99999595 XPANCA= 1.00008357  
RWX= 17.919518 RWY= 25.503929 SHP= 43.423447

THIGH= 28.9520 TLOW= 24.4215 Fe= 0.1070760  
FeO= 0.1671415 KCl= 0.1650441 FeS2= 0.1240458  
MgO= 0.2245880 Li= 0.8505173 Al= 0.2159940  
LiF= 0.3872117 LiBr= 0.1428383 LiCl= 0.2835443  
HPHC= 0.1311827 AHC= 0.3283288 EHC= 0.1643598  
EUT= 0.1971999 SHC= 0.1699713 XHC= 19.64383

CPINS= 0.2015058 CPHPAP= 0.1400  
TSTSTHC= 1.338408 THPHC= 4.399761 TSHC= 0.473583  
TECHC= 4.551178 TINSHC= 3.389670 TINSTHC= 0.569757  
TAHC= 3.555100 TPAPHC= 1.603113  
T1= 297.571503 T2= 302.101990 TEUTFUS= 0.000000

K= 0.3476491547E-03 TAVSTACK= 26.687 TAVINS= 29.939  
TIME1= 1599.99597 TIME2= 1800.02502 INTTIME= 200.02905  
TICASE= 31.4280 TFCASE= 34.9550 TCASE= 33.1915  
DELHT= 0.098205 AVTIME = 1700.010498  
XHC= 19.643827 XPANST= 1.00005257 XPANCA= 1.00012589  
RWX= 17.921036 RWY= 25.506096 SHP= 43.427132

THIGH= 32.8190 TLOW= 28.9520 Fe= 0.1073179  
FeO= 0.1675603 KCl= 0.1650217 FeS2= 0.1248680  
MgO= 0.2258897 Li= 0.8535382 Al= 0.2164546  
LiF= 0.3894671 LiBr= 0.1429843 LiCl= 0.2838811  
HPHC= 0.1314581 AHC= 0.3292432 EHC= 0.1651725  
EUT= 0.1975897 SHC= 0.1707883 XHC= 16.81247  
CPINS= 0.2018754 CPHPAP= 0.1400  
TSTSTHC= 1.144982 THPHC= 3.763309 TSHC= 0.406170  
TECHC= 3.903874 TINSHC= 2.898564 TINSTHC= 0.487416  
TAHC= 3.042912 TPAPHC= 1.368339  
T1= 302.101990 T2= 305.968994 TEUTFUS= 0.000000

K= 0.3457869752E-03 TAVSTACK= 30.885 TAVINS= 33.685  
TIME1= 1800.02502 TIME2= 2000.01099 INTTIME= 199.98596  
TICASE= 34.9550 TFCASE= 38.0120 TCASE= 36.4835  
DELHT= 0.084068 AVTIME = 1900.018066  
XHC= 16.812468 XPANST= 1.00009978 XPANCA= 1.00016296  
RWX= 17.922235 RWY= 25.507814 SHP= 43.430050

THIGH= 36.2185 TLOW= 32.8190 Fe= 0.1075380  
FeO= 0.1679129 KCl= 0.1650126 FeS2= 0.1255540  
MgO= 0.2269793 Li= 0.8562734 Al= 0.2168532  
LiF= 0.3913652 LiBr= 0.1431106 LiCl= 0.2841725  
HPHC= 0.1317006 AHC= 0.3300557 EHC= 0.1658534  
EUT= 0.1979218 SHC= 0.1714953 XHC= 14.81452  
CPINS= 0.2021982 CPHPAP= 0.1400  
TSTSTHC= 1.008624 THPHC= 3.314450 TSHC= 0.358544  
TECHC= 3.446064 TINSHC= 2.552219 TINSTHC= 0.429369  
TAHC= 2.681643 TPAPHC= 1.202915  
T1= 305.968994 T2= 309.368500 TEUTFUS= 0.000000

K= 0.3498468723E-03 TAVSTACK= 34.519 TAVINS= 36.956  
TIME1= 2000.01099 TIME2= 2199.99609 INTTIME= 199.98511  
TICASE= 38.0120 TFCASE= 40.7760 TCASE= 39.3940  
DELHT= 0.074078 AVTIME = 2100.003418  
XHC= 14.814524 XPANST= 1.00014079 XPANCA= 1.00019598  
RWX= 17.923250 RWY= 25.509268 SHP= 43.432518

THIGH= 39.1795 TLOW= 36.2185 Fe= 0.1077386  
FeO= 0.1682145 KCl= 0.1650123 FeS2= 0.1261359  
MgO= 0.2279063 Li= 0.8587570 Al= 0.2172022  
LiF= 0.3929881 LiBr= 0.1432213 LiCl= 0.2844277  
HPHC= 0.1319161 AHC= 0.3307827 ECHC= 0.1664331  
EUT= 0.1982089 SHC= 0.1721142 XHC= 12.93004  
CPINS= 0.2024852 CPHPAP= 0.1400  
TSTSTHC= 0.880159 THPHC= 2.891637 TSHC= 0.313422  
TEHC= 3.012043 TINSHC= 2.226160 TINSTHC= 0.374682  
TAHC= 2.340879 TPAPHC= 1.047749  
T1= 309.368500 T2= 312.329498 TEUTFUS= 0.000000

K= 0.3435873368E-03 TAVSTACK= 37.699 TAVINS= 39.865  
TIME1= 2199.99609 TIME2= 2400.00000 INTTIME= 200.00391  
TICASE= 40.7760 TFCASE= 43.2860 TCASE= 42.0310  
DELTH= 0.064649 AVTIME = 2299.998047  
XHC= 12.930037 XPANST= 1.00017679 XPANCA= 1.00022614  
RWX= 17.924105 RWY= 25.510477 SHP= 43.434582

THIGH= 41.7665 TLOW= 39.1795 Fe= 0.1079190  
FeO= 0.1684724 KCl= 0.1650174 FeS2= 0.1266299  
MgO= 0.2286953 Li= 0.8609849 Al= 0.2175064  
LiF= 0.3943751 LiBr= 0.1433177 LiCl= 0.2846501  
HPHC= 0.1321061 AHC= 0.3314276 ECHC= 0.1669267  
EUT= 0.1984565 SHC= 0.1726537 XHC= 11.31700  
CPINS= 0.2027393 CPHPAP= 0.1400  
TSTSTHC= 0.770277 THPHC= 2.530043 TSHC= 0.274694  
TEHC= 2.639408 TINSHC= 1.947423 TINSTHC= 0.327905  
TAHC= 2.049198 TPAPHC= 0.915412  
T1= 312.329498 T2= 314.916504 TEUTFUS= 0.000000

K= 0.3311234468E-03 TAVSTACK= 40.473 TAVINS= 42.440  
TIME1= 2400.00000 TIME2= 2600.01099 INTTIME= 200.01099  
TICASE= 43.2860 TFCASE= 45.5280 TCASE= 44.4070  
DELTH= 0.056582 AVTIME = 2500.005371  
XHC= 11.316997 XPANST= 1.00020826 XPANCA= 1.00025308  
RWX= 17.924828 RWY= 25.511511 SHP= 43.436340

THIGH= 44.1290 TLOW= 41.7665 Fe= 0.1080846  
FeO= 0.1686984 KCl= 0.1650262 FeS2= 0.1270603  
MgO= 0.2293842 Li= 0.8630244 Al= 0.2177780  
LiF= 0.3955908 LiBr= 0.1434038 LiCl= 0.2848486  
HPHC= 0.1322774 AHC= 0.3320121 ECHC= 0.1673580  
EUT= 0.1986754 SHC= 0.1731354 XHC= 10.35129  
CPINS= 0.2029673 CPHPAP= 0.1400  
TSTSTHC= 0.704507 THPHC= 2.313465 TSHC= 0.251554  
TEHC= 2.416571 TINSHC= 1.780412 TINSTHC= 0.299907  
TAHC= 1.874655 TPAPHC= 0.835966  
T1= 314.916504 T2= 317.278992 TEUTFUS= 0.000000

K= 0.3304246347E-03 TAVSTACK= 42.948 TAVINS= 44.751  
TIME1= 2600.01099 TIME2= 2799.99609 INTTIME= 199.98511

TICASE= 45.5280 TFCASE= 47.5800 TCASE= 46.5540  
DELTH= 0.051760 AVTIME = 2700.003418  
XHC= 10.351294 XPANST= 1.00023663 XPANCA= 1.00027776  
RWX= 17.925463 RWY= 25.512419 SHP= 43.437881

THIGH= 46.2325 TLOW= 44.1290 Fe= 0.1082373  
FeO= 0.1688993 KCl= 0.1650375 FeS2= 0.1274405  
MgO= 0.2299941 Li= 0.8649021 Al= 0.2180229  
LiF= 0.3966708 LiBr= 0.1434814 LiCl= 0.2850277  
HPHC= 0.1324333 AHC= 0.3325460 ECHC= 0.1677400  
EUT= 0.1988712 SHC= 0.1735698 XHC= 9.22967  
CPINS= 0.2031714 CPHPAP= 0.1400  
TSTSTHC= 0.628166 THPHC= 2.062294 TSHC= 0.224541  
TECHC= 2.156581 TINSHC= 1.586841 TINSTHC= 0.267409  
TAHC= 1.671843 TPAPHC= 0.744329  
T1= 317.278992 T2= 319.382507 TEUTFUS= 0.000000

K= 0.3240774968E-03 TAVSTACK= 45.181 TAVINS= 46.820  
TIME1= 2799.99609 TIME2= 3000.01807 INTTIME= 200.02197  
TICASE= 47.5800 TFCASE= 49.3370 TCASE= 48.4585  
DELTH= 0.046143 AVTIME = 2900.007080  
XHC= 9.229666 XPANST= 1.00026202 XPANCA= 1.00029945  
RWX= 17.926046 RWY= 25.513256 SHP= 43.439301

THIGH= 48.1295 TLOW= 46.2325 Fe= 0.1083768  
FeO= 0.1690770 KCl= 0.1650500 FeS2= 0.1277751  
MgO= 0.2305318 Li= 0.8666144 Al= 0.2182425  
LiF= 0.3976257 LiBr= 0.1435510 LiCl= 0.2851882  
HPHC= 0.1325740 AHC= 0.3330297 ECHC= 0.1680770  
EUT= 0.1990455 SHC= 0.1739591 XHC= 8.33422  
CPINS= 0.2033523 CPHPAP= 0.1400  
TSTSTHC= 0.567217 THPHC= 1.861775 TSHC= 0.202947  
TECHC= 1.948734 TINSHC= 1.432304 TINSTHC= 0.241463  
TAHC= 1.509879 TPAPHC= 0.671244  
T1= 319.382507 T2= 321.279480 TEUTFUS= 0.000000

K= 0.3257629287E-03 TAVSTACK= 47.181 TAVINS= 48.653  
TIME1= 3000.01807 TIME2= 3199.99609 INTTIME= 199.97803  
TICASE= 49.3370 TFCASE= 50.9150 TCASE= 50.1260  
DELTH= 0.041676 AVTIME = 3100.007080  
XHC= 8.334223 XPANST= 1.00028491 XPANCA= 1.00031865  
RWX= 17.926588 RWY= 25.514021 SHP= 43.440609

THIGH= 49.7450 TLOW= 48.1295 Fe= 0.1085009  
FeO= 0.1692310 KCl= 0.1650628 FeS2= 0.1280640  
MgO= 0.2309967 Li= 0.8681360 Al= 0.2184349  
LiF= 0.3984536 LiBr= 0.1436120 LiCl= 0.2853289  
HPHC= 0.1326981 AHC= 0.3334574 ECHC= 0.1683685  
EUT= 0.1991974 SHC= 0.1743004 XHC= 7.10541  
CPINS= 0.2035107 CPHPAP= 0.1400  
TSTSTHC= 0.483609 THPHC= 1.587018 TSHC= 0.173174  
TECHC= 1.662469 TINSHC= 1.220736 TINSTHC= 0.205871

TAHC= 1.287501 TPAPHC= 0.571648  
T1= 321.279480 T2= 322.894989 TEUTFUS= 0.000000

K= 0.3095124266E-03 TAVSTACK= 48.937 TAVINS= 50.258  
TIME1= 3199.99609 TIME2= 3399.99609 INTTIME= 200.00000  
TICASE= 50.9150 TFCASE= 52.2440 TCASE= 51.5795  
DELTHT= 0.035527 AVTIME = 3299.996094  
XHC= 7.105405 XPANST= 1.00030494 XPANCA= 1.00033534  
RWX= 17.927065 RWY= 25.514704 SHP= 43.441769

THIGH= 51.1725 TLOW= 49.7450 Fe= 0.1086108  
FeO= 0.1693632 KCl= 0.1650759 FeS2= 0.1283105  
MgO= 0.2313942 Li= 0.8694816 Al= 0.2186022  
LiF= 0.3991636 LiBr= 0.1436650 LiCl= 0.2854512  
HPHC= 0.1328067 AHC= 0.3338331 ECHC= 0.1686178  
EUT= 0.1993285 SHC= 0.1745971 XHC= 6.28459  
CPINS= 0.2036461 CPHPAP= 0.1400  
TSTSTHC= 0.427767 THPHC= 1.403493 TSHC= 0.153283  
TECHC= 1.471192 TINSHC= 1.079403 TINSTHC= 0.182099  
TAHC= 1.138963 TPAPHC= 0.505128  
T1= 322.894989 T2= 324.322510 TEUTFUS= 0.000000

K= 0.3085833450E-03 TAVSTACK= 50.459 TAVINS= 51.631  
TIME1= 3399.99609 TIME2= 3600.01709 INTTIME= 200.02100  
TICASE= 52.2440 TFCASE= 53.3610 TCASE= 52.8025  
DELTHT= 0.031420 AVTIME = 3500.006592  
XHC= 6.284587 XPANST= 1.00032246 XPANCA= 1.00034940  
RWX= 17.927500 RWY= 25.515326 SHP= 43.442825

THIGH= 52.5060 TLOW= 51.1725 Fe= 0.1087109  
FeO= 0.1694820 KCl= 0.1650884 FeS2= 0.1285315  
MgO= 0.2317509 Li= 0.8707055 Al= 0.2187534  
LiF= 0.3998016 LiBr= 0.1437129 LiCl= 0.2855617  
HPHC= 0.1329052 AHC= 0.3341741 ECHC= 0.1688416  
EUT= 0.1994467 SHC= 0.1748653 XHC= 5.87587  
CPINS= 0.2037668 CPHPAP= 0.1400  
TSTSTHC= 0.399960 THPHC= 1.312023 TSHC= 0.143407  
TECHC= 1.376114 TINSHC= 1.008905 TINSTHC= 0.170262  
TAHC= 1.065032 TPAPHC= 0.471858  
T1= 324.322510 T2= 325.656006 TEUTFUS= 0.000000

K= 0.3332094930E-03 TAVSTACK= 51.839 TAVINS= 52.854  
TIME1= 3600.01709 TIME2= 3799.99609 INTTIME= 199.97900  
TICASE= 53.3610 TFCASE= 54.3770 TCASE= 53.8690  
DELTHT= 0.029382 AVTIME = 3700.006592  
XHC= 5.875873 XPANST= 1.00033832 XPANCA= 1.00036168  
RWX= 17.927906 RWY= 25.515905 SHP= 43.443810

THIGH= 53.6510 TLOW= 52.5060 Fe= 0.1088019  
FeO= 0.1695878 KCl= 0.1651006 FeS2= 0.1287277  
MgO= 0.2320682 Li= 0.8718180 Al= 0.2188894

LiF= 0.4003701 LiBr= 0.1437560 LiCl= 0.2856611  
HPHC= 0.1329941 AHC= 0.3344828 EHC= 0.1690406  
EUT= 0.1995524 SHC= 0.1751064 XHC= 5.04922  
CPINS= 0.2038732 CPHPAP= 0.1400  
TSTSTHC= 0.343708 THPHC= 1.127305 TSHC= 0.123304  
TEHC= 1.182975 TINSHC= 0.866735 TINSTHC= 0.146316  
TAHC= 0.915320 TPAPHC= 0.405154  
T1= 325.656006 T2= 326.800995 TEUTFUS= 0.000000

K= 0.3403904266E-03 TAVSTACK= 53.078 TAVINS= 53.932  
TIME1= 3799.99609 TIME2= 4000.01709 INTTIME= 200.02100  
TICASE= 54.3770 TFCASE= 55.1940 TCASE= 54.7855  
DELTH= 0.025243 AVTIME = 3900.006592  
XHC= 5.049217 XPANST= 1.00035262 XPANCA= 1.00037229  
RWX= 17.928297 RWY= 25.516462 SHP= 43.444759

THIGH= 54.6490 TLOW= 53.6510 Fe= 0.1088818  
FeO= 0.1696786 KCl= 0.1651122 FeS2= 0.1288953  
MgO= 0.2323394 Li= 0.8727936 Al= 0.2190071  
LiF= 0.4008575 LiBr= 0.1437933 LiCl= 0.2857472  
HPHC= 0.1330716 AHC= 0.3347524 EHC= 0.1692109  
EUT= 0.1996436 SHC= 0.1753153 XHC= 4.40395  
CPINS= 0.2039634 CPHPAP= 0.1400  
TSTSTHC= 0.299809 THPHC= 0.983175 TSHC= 0.107605  
TEHC= 1.032166 TINSHC= 0.755814 TINSTHC= 0.127628  
TAHC= 0.798471 TPAPHC= 0.353148  
T1= 326.800995 T2= 327.799011 TEUTFUS= 0.000000

K= 0.3638773633E-03 TAVSTACK= 54.150 TAVINS= 54.847  
TIME1= 4000.01709 TIME2= 4199.99902 INTTIME= 199.98193  
TICASE= 55.1940 TFCASE= 55.8920 TCASE= 55.5430  
DELTH= 0.022022 AVTIME = 4100.007812  
XHC= 4.403946 XPANST= 1.00036490 XPANCA= 1.00038099  
RWX= 17.928640 RWY= 25.516954 SHP= 43.445595

THIGH= 55.5030 TLOW= 54.6490 Fe= 0.1089499  
FeO= 0.1697567 KCl= 0.1651218 FeS2= 0.1290398  
MgO= 0.2325731 Li= 0.8736264 Al= 0.2191081  
LiF= 0.4012771 LiBr= 0.1438254 LiCl= 0.2858211  
HPHC= 0.1331379 AHC= 0.3349828 EHC= 0.1693576  
EUT= 0.1997218 SHC= 0.1754944 XHC= 3.77067  
CPINS= 0.2040430 CPHPAP= 0.1400  
TSTSTHC= 0.256698 THPHC= 0.841693 TSHC= 0.092169  
TEHC= 0.883959 TINSHC= 0.646980 TINSTHC= 0.109276  
TAHC= 0.683699 TPAPHC= 0.302178  
T1= 327.799011 T2= 328.652985 TEUTFUS= 0.000000

K= 0.3756626102E-03 TAVSTACK= 55.076 TAVINS= 55.653  
TIME1= 4199.99902 TIME2= 4400.02490 INTTIME= 200.02588  
TICASE= 55.8920 TFCASE= 56.5700 TCASE= 56.2310  
DELTH= 0.018851 AVTIME = 4300.011719  
XHC= 3.770670 XPANST= 1.00037563 XPANCA= 1.00038886

RWX= 17.928932 RWY= 25.517374 SHP= 43.446304

THIGH= 56.2320 TLOW= 55.5030 Fe= 0.1090103  
FeO= 0.1698229 KCl= 0.1651315 FeS2= 0.1291613  
MgO= 0.2327703 Li= 0.8743626 Al= 0.2191955  
LiF= 0.4016328 LiBr= 0.1438530 LiCl= 0.2858849  
HPHC= 0.1331958 AHC= 0.3351849 EHC= 0.1694815  
EUT= 0.1997888 SHC= 0.1756493 XHC= 3.22038  
CPINS= 0.2041120 CPHPAP= 0.1400  
TSTSTHC= 0.219255 THPHC= 0.718833 TSHC= 0.078750  
TECHC= 0.755154 TINSHC= 0.552489 TINSTHC= 0.093336  
TAHC= 0.583999 TPAPHC= 0.257958  
T1= 328.652985 T2= 329.381989 TEUTFUS= 0.000000

K= 0.3823267471E-03 TAVSTACK= 55.868 TAVINS= 56.352  
TIME1= 4400.02490 TIME2= 4599.99609 INTTIME= 199.97119  
TICASE= 56.5700 TFCASE= 57.1040 TCASE= 56.8370  
DELTH= 0.016104 AVTIME = 4500.010742  
XHC= 3.220382 XPANST= 1.00038469 XPANCA= 1.00039589  
RWX= 17.929165 RWY= 25.517702 SHP= 43.446869

THIGH= 56.9030 TLOW= 56.2320 Fe= 0.1090632  
FeO= 0.1698815 KCl= 0.1651398 FeS2= 0.1292689  
MgO= 0.2329448 Li= 0.8750083 Al= 0.2192724  
LiF= 0.4019472 LiBr= 0.1438774 LiCl= 0.2859412  
HPHC= 0.1332467 AHC= 0.3353624 EHC= 0.1695911  
EUT= 0.1998480 SHC= 0.1757857 XHC= 2.96548  
CPINS= 0.2041720 CPHPAP= 0.1400  
TSTSTHC= 0.201905 THPHC= 0.661881 TSHC= 0.072540  
TECHC= 0.695508 TINSHC= 0.508671 TINSTHC= 0.085950  
TAHC= 0.537809 TPAPHC= 0.237430  
T1= 329.381989 T2= 330.052979 TEUTFUS= 0.000000

K= 0.4347392241E-03 TAVSTACK= 56.567 TAVINS= 56.960  
TIME1= 4599.99609 TIME2= 4799.99609 INTTIME= 200.00000  
TICASE= 57.1040 TFCASE= 57.6010 TCASE= 57.3525  
DELTH= 0.014827 AVTIME = 4699.996094  
XHC= 2.965475 XPANST= 1.00039279 XPANCA= 1.00040197  
RWX= 17.929382 RWY= 25.518015 SHP= 43.447395

THIGH= 57.4560 TLOW= 56.9030 Fe= 0.1091096  
FeO= 0.1699324 KCl= 0.1651473 FeS2= 0.1293622  
MgO= 0.2330961 Li= 0.8755739 Al= 0.2193395  
LiF= 0.4022203 LiBr= 0.1438987 LiCl= 0.2859902  
HPHC= 0.1332911 AHC= 0.3355177 EHC= 0.1696861  
EUT= 0.1998995 SHC= 0.1759047 XHC= 2.44491  
CPINS= 0.2042244 CPHPAP= 0.1400  
TSTSTHC= 0.166474 THPHC= 0.545684 TSHC= 0.059825  
TECHC= 0.573538 TINSHC= 0.419339 TINSTHC= 0.070868  
TAHC= 0.443451 TPAPHC= 0.195682  
T1= 330.052979 T2= 330.605988 TEUTFUS= 0.000000



K= 0.4508614657E-03 TAVSTACK= 57.180 TAVINS= 57.492  
TIME1= 4799.99609 TIME2= 5000.01318 INTTIME= 200.01709  
TICASE= 57.6010 TFCASE= 58.0060 TCASE= 57.8035  
DELTH= 0.012224 AVTIME = 4900.004883  
XHC= 2.444914 XPANST= 1.00039983 XPANCA= 1.00040710  
RWX= 17.929575 RWY= 25.518290 SHP= 43.447865

THIGH= 58.3995 TLOW= 57.4560 Fe= 0.1091665  
FeO= 0.1699943 KCl= 0.1651566 FeS2= 0.1294755  
MgO= 0.2332802 Li= 0.8762671 Al= 0.2194213  
LiF= 0.4025525 LiBr= 0.1439246 LiCl= 0.2860501  
HPHC= 0.1333455 AHC= 0.3357077 ECHC= 0.1698017  
EUT= 0.1999622 SHC= 0.1760499 XHC= 4.17332  
CPINS= 0.2042893 CPHPAP= 0.1400  
TSTSTHC= 0.284177 THPHC= 0.931394 TSHC= 0.102155  
TECHC= 0.979203 TINSHC= 0.715678 TINSTHC= 0.120973  
TAHC= 0.757019 TPAPHC= 0.333862  
T1= 330.605988 T2= 331.549500 TEUTFUS= 0.000000

K= 0.5423685652E-03 TAVSTACK= 57.928 TAVINS= 58.149  
TIME1= 5000.01318 TIME2= 5400.00879 INTTIME= 399.99561  
TICASE= 58.0060 TFCASE= 58.7350 TCASE= 58.3705  
DELTH= 0.010433 AVTIME = 5200.010742  
XHC= 4.173316 XPANST= 1.00040841 XPANCA= 1.00041366  
RWX= 17.929800 RWY= 25.518612 SHP= 43.448410

THIGH= 59.0660 TLOW= 58.3995 Fe= 0.1092286  
FeO= 0.1700609 KCl= 0.1651673 FeS2= 0.1295971  
MgO= 0.2334778 Li= 0.8770243 Al= 0.2195101  
LiF= 0.4029099 LiBr= 0.1439527 LiCl= 0.2861149  
HPHC= 0.1334046 AHC= 0.3359146 ECHC= 0.1699259  
EUT= 0.2000299 SHC= 0.1762073 XHC= 2.94961  
CPINS= 0.2043595 CPHPAP= 0.1400  
TSTSTHC= 0.200859 THPHC= 0.658236 TSHC= 0.072227  
TECHC= 0.692223 TINSHC= 0.505734 TINSTHC= 0.085505  
TAHC= 0.535093 TPAPHC= 0.235842  
T1= 331.549500 T2= 332.216003 TEUTFUS= 0.000000

K= 0.6609963020E-03 TAVSTACK= 58.733 TAVINS= 58.861  
TIME1= 5400.00879 TIME2= 5800.01904 INTTIME= 400.01025  
TICASE= 58.7350 TFCASE= 59.2440 TCASE= 58.9895  
DELTH= 0.007374 AVTIME = 5600.013672  
XHC= 2.949606 XPANST= 1.00041783 XPANCA= 1.00042081  
RWX= 17.930048 RWY= 25.518970 SHP= 43.449020

THIGH= 59.7285 TLOW= 59.0660 Fe= 0.1092788  
FeO= 0.1701151 KCl= 0.1651757 FeS2= 0.1296963  
MgO= 0.2336389 Li= 0.8776357 Al= 0.2195821  
LiF= 0.4032010 LiBr= 0.1439755 LiCl= 0.2861675  
HPHC= 0.1334525 AHC= 0.3360820 ECHC= 0.1700271  
EUT= 0.2000849 SHC= 0.1763349 XHC= 2.93309

CPINS= 0.2044185 CPHPAP= 0.1400  
TSTSTHC= 0.199737 THPHC= 0.654492 TSHC= 0.071843  
TECHC= 0.688448 TINSHC= 0.502823 TINSTHC= 0.085027  
TAHC= 0.532124 TPAPHC= 0.234417  
T1= 332.216003 T2= 332.878479 TEUTFUS= 0.000000

K= 0.9241293883E-03 TAVSTACK= 59.397 TAVINS= 59.458  
TIME1= 5800.01904 TIME2= 6400.02197 INTTIME= 600.00293  
TICASE= 59.2440 TFCASE= 59.7940 TCASE= 59.5190  
DELHT= 0.004888 AVTIME = 6100.020508  
XHC= 2.933091 XPANST= 1.00042546 XPANCA= 1.00042701  
RWX= 17.930237 RWY= 25.519234 SHP= 43.449471

THIGH= 60.1025 TLOW= 59.7285 Fe= 0.1093196  
FeO= 0.1701577 KCl= 0.1651831 FeS2= 0.1297736  
MgO= 0.2337647 Li= 0.8781325 Al= 0.2196395  
LiF= 0.4034294 LiBr= 0.1439938 LiCl= 0.2862096  
HPHC= 0.1334910 AHC= 0.3362171 EHC= 0.1701063  
EUT= 0.2001285 SHC= 0.1764368 XHC= 1.65636  
CPINS= 0.2044648 CPHPAP= 0.1400  
TSTSTHC= 0.112810 THPHC= 0.369623 TSHC= 0.040585  
TECHC= 0.388868 TINSHC= 0.283950 TINSTHC= 0.048023  
TAHC= 0.300550 TPAPHC= 0.132348  
T1= 332.878479 T2= 333.252502 TEUTFUS= 0.000000

K= 0.3971423954E-02 TAVSTACK= 59.916 TAVINS= 59.927  
TIME1= 6400.02197 TIME2= 6800.00488 INTTIME= 399.98291  
TICASE= 59.7940 TFCASE= 60.0850 TCASE= 59.9395  
DELHT= 0.004141 AVTIME = 6600.013672  
XHC= 1.656363 XPANST= 1.00043154 XPANCA= 1.00043178  
RWX= 17.930389 RWY= 25.519451 SHP= 43.449841

THIGH= 60.9405 TLOW= 60.1025 Fe= 0.1093671  
FeO= 0.1702072 KCl= 0.1651918 FeS2= 0.1298636  
MgO= 0.2339114 Li= 0.8787099 Al= 0.2197063  
LiF= 0.4036954 LiBr= 0.1440149 LiCl= 0.2862584  
HPHC= 0.1335358 AHC= 0.3363743 EHC= 0.1701985  
EUT= 0.2001792 SHC= 0.1765553 XHC= 3.71271  
CPINS= 0.2045167 CPHPAP= 0.1400  
TSTSTHC= 0.252856 THPHC= 0.828400 TSHC= 0.090989  
TECHC= 0.871714 TINSHC= 0.636339 TINSTHC= 0.107640  
TAHC= 0.673683 TPAPHC= 0.296520  
T1= 333.252502 T2= 334.090485 TEUTFUS= 0.000000

K= 0.2425040584E-03 TAVSTACK= 60.521 TAVINS= 60.454  
TIME1= 6800.00488 TIME2= 9409.99609 INTTIME= 2609.99121  
TICASE= 60.0850 TFCASE= 60.6880 TCASE= 60.3865  
DELHT= 0.001423 AVTIME = 8105.000488  
XHC= 3.712714 XPANST= 1.00043857 XPANCA= 1.00043702  
RWX= 17.930580 RWY= 25.519726 SHP= 43.450306

HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2  
 ECMASS = 6.112 ANODEMASS = 2.390  
 HPELLETMASS = 7.403 STEELSTACKMASS = 2.759  
 INSMASS = 7.426 HEAT PAPER MASS = 5.056  
 SULFUR MASS = 0.615 MASS STEEL IN INS = 2.349

#### A-4. Graphical Global Thermal Conductivity Values for the LCCM Thermal Insulation Package

The exact effect of the gas composition of operating atmosphere thermal battery gas mixtures on the global thermal conductivity of the thermal insulation package must be known to optimize battery operation in the field. Global thermal conductivity values measured for the LCCM thermal insulation package for gases and gas mixtures are shown in figures A-1 through A-4 using more examples and clearer detail than could be shown in figure 1 of the main report. All of the values shown were calculated as shown in sections A-1 through A-3. For the transient experiments, measured thermal conductivity values from  $-20$  to  $+40$  °C most closely approach the quasi-steady-state thermal conductivity values that will be apply at the insulation temperatures shown.

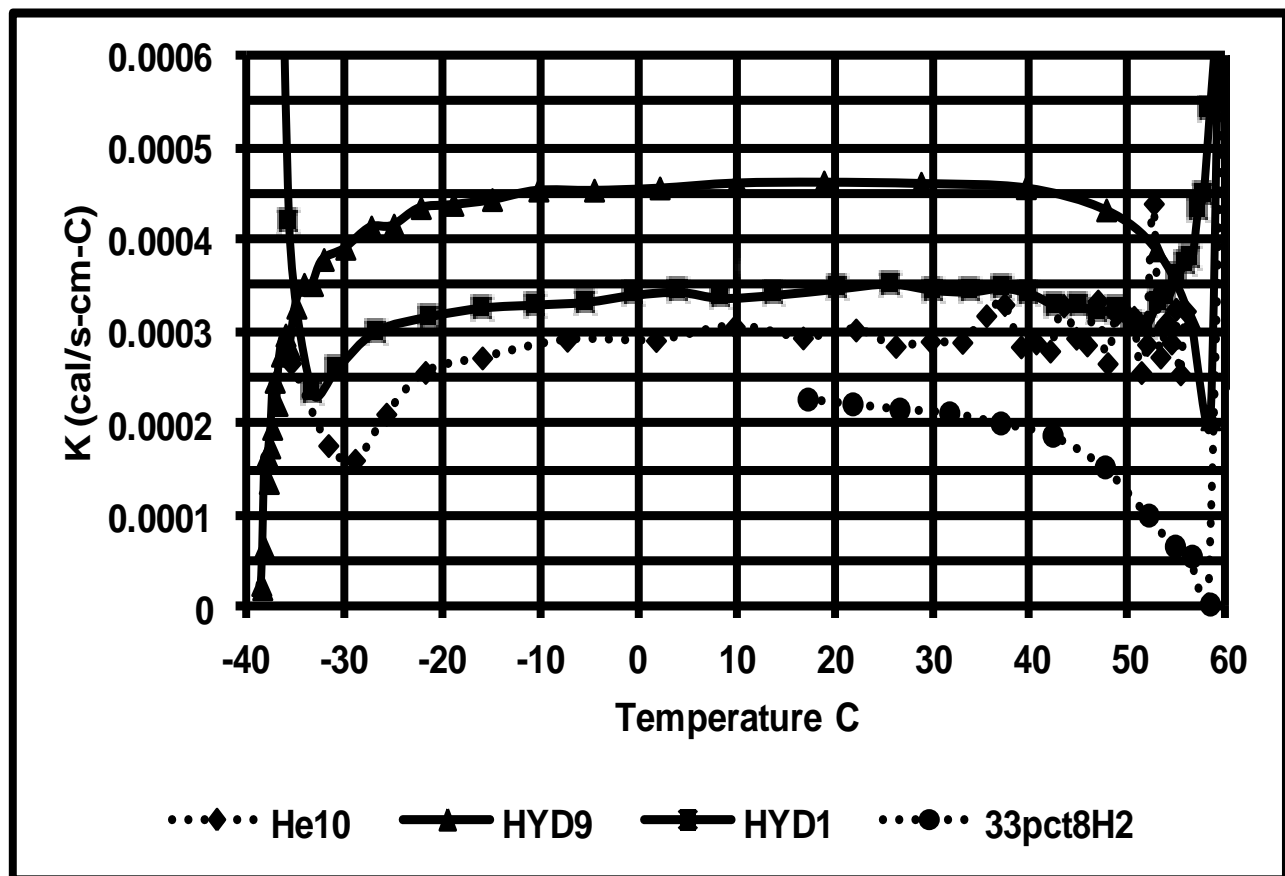


Figure A-1. LCCM global thermal insulation package thermal conductivity values for helium at 10 atmospheres absolute, for hydrogen at 9 atmospheres and at 1 atmosphere absolute, and for a 33/67 volume percent hydrogen/air mixture at 8 atmospheres absolute.

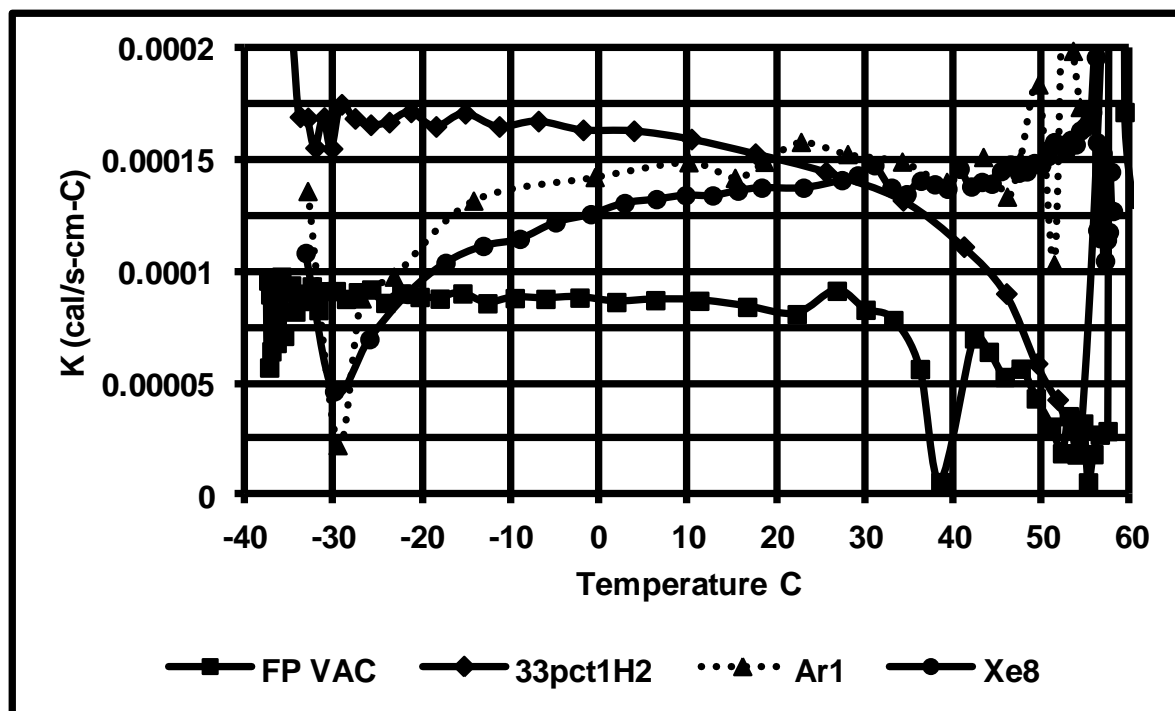


Figure A-2. LCCM global thermal insulation package thermal conductivity values for a fore pump vacuum atmosphere (~6.7 Pa), for a 33/67 volume percent hydrogen/air mixture at 1 atmosphere absolute, for argon at 1 atmosphere absolute, and for xenon at 8 atmospheres absolute.

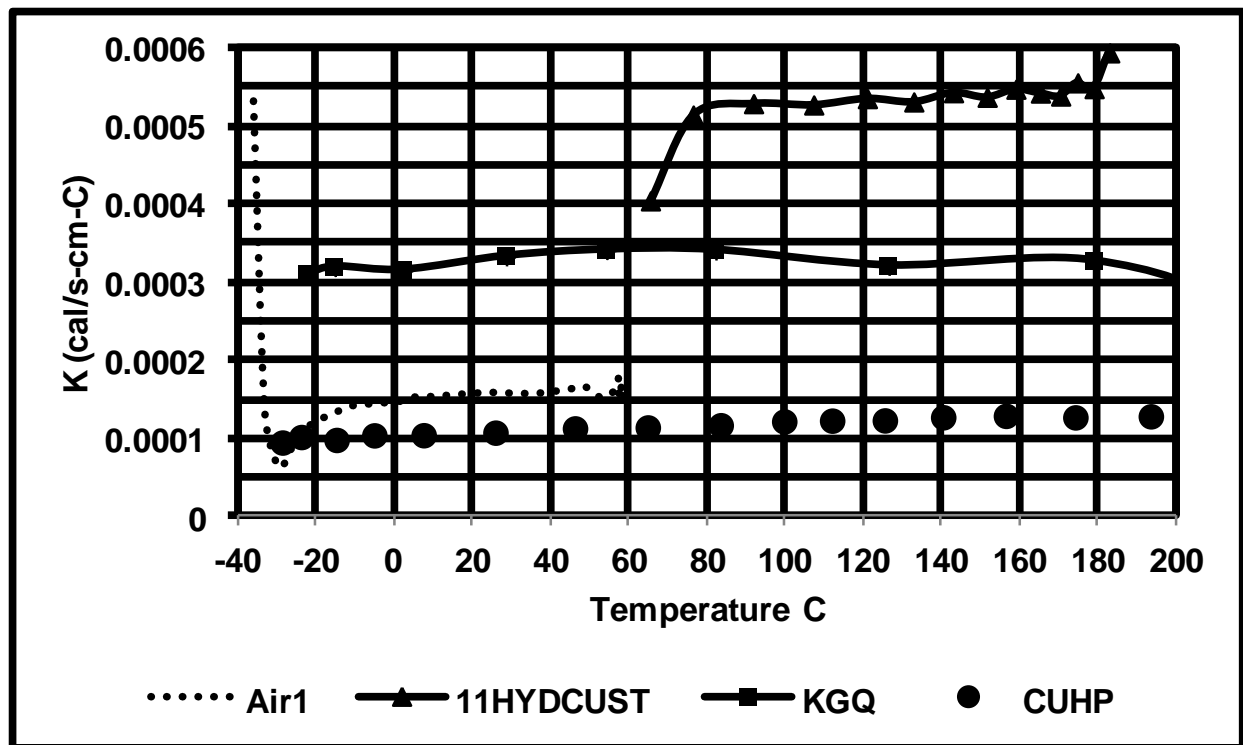


Figure A-3. LCCM global thermal insulation package thermal conductivity values for air at one atmosphere absolute, for pure hydrogen at 11 atmospheres absolute as measured using the copper-heat pellet high temperature transient experiment, for the LCCM thermal battery GPS9Q quasi-steady-state experiment, hermetically sealed containing 1 atmosphere of dry room air and then initiated as the cell stack cooled from nominally 550 °C to -40 °C, and for a the copper-heat pellet stack quasi-steady-state experiment built into an LCCM configuration as the copper disks cooled from nominally 500 °C to -40 °C in a fore pump vacuum.

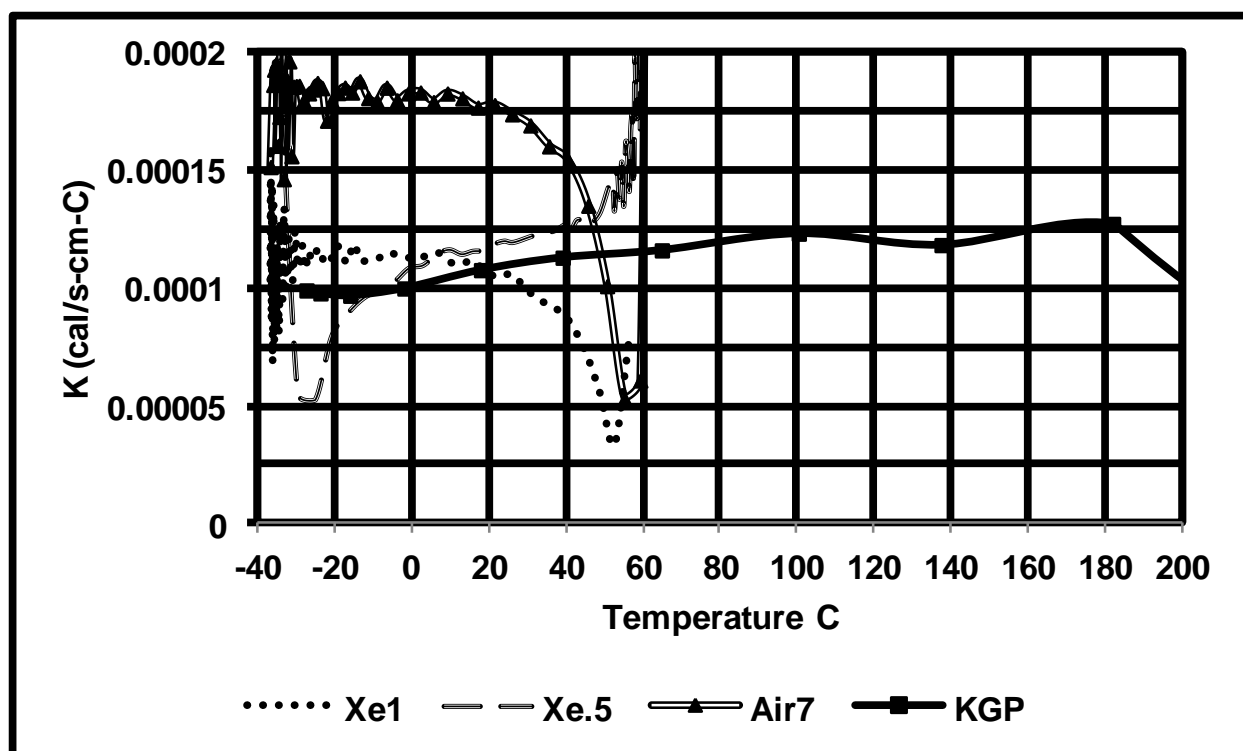


Figure A-4. LCCM global thermal insulation package thermal conductivity values for xenon at 1 atmosphere absolute, for xenon at 0.5 atmosphere absolute, for air at 7 atmospheres absolute, and for the LCCM thermal battery GPS9P quasi-steady-state experiment as the cell stack cooled from nominally 550 °C to -40 °C in a fore pump vacuum as described in reference 1. The Xe.5 heating curve appears to become increasingly contaminated with higher thermal conductivity gases as it approaches 60 °C near the end of the experiment.

#### A-5. Tabular Global Thermal Conductivity Values for the LCCM Thermal Insulation Package

Tabular values of the output parameter K measurements (in cal/s-cm-°C) at the global LCCM thermal insulation package temperatures TAVINS from the Fortran output file shown in section A-3 were used to make the graphs used in figures A-1 through A-4 and in figures 1 and 2 in the main report. Those tabular values are shown for convenience and precision in tables A-1 and A-2. The tabular values shown below are copies of the Excel spreadsheet data originally used to make those graphs.

Table A-1. Tabular global thermal conductivity values for the LCCM thermal insulation package. Thermal conductivity values are shown in cal/s-cm-°C.

TINS C	He10	TINS C	FP VAC	TINS C	HYD9	TINS C	HYD1	TINS C	33pct1H2	TINS C	33pct8H2	TINS C	Ar1
-35.452	0.000266	60.33	0.000129	60.874	0.000774	-38.239	0.002797	60.464	0.000952	61.071	1.107087	-32.987	0.000136
-31.644	0.000177	59.326	0.000172	59.886	0.001117	-37.414	0.00146	57.981	0.000352	60.222	0.001164	-29.592	2.24E-05
-28.917	0.000161	58.252	0.001788	58.326	0.000206	-35.761	0.000423	54.521	2.83E-05	58.273	4.34E-06	-26.872	8.81E-05
-25.73	0.000211	57.41	2.87E-05	56.328	0.000313	-33.399	0.000236	51.765	4.28E-05	56.428	5.65E-05	-23.245	9.78E-05
-21.748	0.000256	56.525	2.71E-05	52.828	0.00039	-30.934	0.000262	49.438	5.9E-05	54.703	6.74E-05	-14.25	0.000132
-15.947	0.000272	55.808	1.83E-05	47.695	0.000433	-26.935	0.000302	45.963	9.03E-05	52.015	0.000101	-0.547	0.000142
-7.285	0.000291	55.197	5.71E-06	39.5	0.000457	-21.431	0.000319	41.163	0.000111	47.555	0.000154	10.056	0.000149
1.775	0.000291	54.654	3.21E-05	28.804	0.000462	-15.878	0.000328	34.285	0.000132	42.225	0.000188	15.294	0.000142
9.809	0.000306	53.901	1.82E-05	18.896	0.000464	-10.52	0.000332	25.573	0.000145	36.918	0.000201	18.637	0.000149
16.764	0.000294	53.034	3.53E-05	9.966	0.000463	-5.415	0.000335	17.596	0.000153	31.686	0.000212	22.755	0.000155
22.156	0.000303	52.266	1.87E-05	2.151	0.000457	-0.528	0.000342	10.376	0.000159	26.609	0.000217	28.022	0.000153
26.22	0.000285	51.009	3.07E-05	-4.539	0.000455	4.086	0.000345	3.878	0.000163	21.82	0.000222	34.178	0.000149
29.795	0.00029	49.302	4.33E-05	-10.216	0.000455	8.334	0.000339	-1.856	0.000164	17.242	0.000227	39.223	0.00014
33.017	0.000289	47.587	5.66E-05	-14.945	0.000444	13.864	0.000342	-6.919	0.000167			43.349	0.000151
35.463	0.000318	45.781	5.29E-05	-18.889	0.000439	20.277	0.000349	-11.34	0.000165			46.04	0.000134
37.317	0.00033	43.99	6.42E-05	-22.21	0.000436	25.546	0.000354	-15.186	0.000171			47.515	0.00015
38.996	0.000284	42.322	7.02E-05	-24.969	0.000417	29.939	0.000348	-18.482	0.000165			49.593	0.000184
40.535	0.000288	38.511	5.82E-06	-27.265	0.000415	33.685	0.000346	-21.317	0.000172			51.353	0.000103
41.974	0.00028	36.206	5.65E-05	-29.905	0.000391	36.956	0.00035	-23.77	0.000167			52.373	0.000229
43.354	0.000329	33.197	7.84E-05	-32.109	0.000379	39.865	0.000344	-25.859	0.000166			53.494	0.000199
44.629	0.000294	30.061	8.3E-05	-33.209	0.000352	42.44	0.000331	-27.629	0.000169			54.268	0.000174
45.733	0.000286	26.811	9.15E-05	-34.119	0.000352	44.751	0.00033	-29.15	0.000175				
46.837	0.000334	22.281	8.1E-05	-34.895	0.000327	46.82	0.000324	-30.22	0.000155				
47.834	0.000266	16.682	8.43E-05	-35.503	0.000282	48.653	0.000326	-31.118	0.000169				
48.739	0.00032	11.273	8.7E-05	-36.009	0.000297	50.258	0.00031	-32.082	0.000156				
49.637	0.000321	6.3	8.73E-05	-36.465	0.000275	51.631	0.000309	-32.958	0.000169				
50.513	0.000316	1.9	8.65E-05	-36.82	0.000222	52.854	0.000333	-33.838	0.000169				
51.267	0.000256	-2.262	8.84E-05	-37.108	0.000247	53.932	0.00034	-34.495	0.000202				
51.864	0.000287	-6.108	8.79E-05	-37.365	0.000196	54.847	0.000364						
52.545	0.00044	-9.576	8.82E-05	-37.565	0.000175	55.653	0.000376						
53.221	0.000273	-12.666	8.59E-05	-37.71	0.000137	56.352	0.000382						
53.831	0.00031	-15.489	9.03E-05	-37.844	0.000165	56.96	0.000435						
54.344	0.000288	-18.054	8.8E-05	-37.987	0.000164	57.492	0.000451						
54.799	0.000325	-20.32	8.87E-05	-38.194	6.59E-05	58.149	0.000542						
55.259	0.000255	-22.389	9.03E-05	-38.378	2.09E-05	58.861	0.000661						
55.818	0.000323	-24.2	8.61E-05	-38.474	2.56E-05	59.458	0.000924						
		-25.794	9.21E-05			59.927	0.003971						
		-27.297	9.09E-05			60.454	0.000243						
		-28.637	8.78E-05										
		-29.796	9.14E-05										
		-30.871	9.13E-05										
		-31.751	8.28E-05										
		-32.508	9.35E-05										
		-33.238	9.02E-05										
		-33.851	8.69E-05										
		-34.366	8.22E-05										
		-34.842	9.39E-05										
		-35.298	9.12E-05										
		-35.636	7.13E-05										
		-35.95	9.78E-05										
		-36.267	8.53E-05										
		-36.479	6.81E-05										
		-36.689	9.73E-05										
		-36.92	8.82E-05										
		-37.071	6.44E-05										
		-37.202	8.99E-05										
		-37.323	5.71E-05										
		-37.425	9.61E-05										

Table A-2. Tabular global thermal conductivity values for the LCCM thermal insulation package. Thermal conductivity values are shown in cal/s-cm-°C.

TINS C	Xe8	TINS C	Xe1	TINS C	Xe5	TINS C	Air7	TINS C	Air1	TINS C	11H2CUS1TINS	KGQ	TINS	CUHP	TAVINS	KGP		
-33.201	0.000108	56.439	7.57E-05	-37.919	0.000461	61.46	0.000474	-35.848	0.000532	65.49562	0.000405	231.4773	5.89E-05	225.1663	0.000451	248.8906	0.002405	
-29.984	4.65E-05	52.8	3.34E-05	-34.917	0.000234	59.182	6.1E-05	-32.915	0.000132	76.43825	0.000515	215.7665	0.000254	214.7401	0.000104	226.911	9.88E-05	
-25.998	6.98E-05	49.124	5.49E-05	-29.818	5.56E-05	55.082	5.3E-05	-29.347	6.35E-05	91.869	0.000529	179.0931	0.000327	207.7977	0.000115	181.9988	0.000127	
-21.697	9.01E-05	45.27	7.28E-05	-25.188	5.28E-05	50.55	0.000101	-24.969	9.85E-05	107.2706	0.000528	126.5705	0.000321	193.5389	0.000129	137.4444	0.000118	
-17.399	0.000104	41.229	8.54E-05	-20.969	7.96E-05	45.657	0.000135	-20.465	0.000121	121.0013	0.000536	82.2575	0.000341	174.2216	0.000127	100.35	0.000123	
-13.145	0.000112	37.366	9.14E-05	-16.754	8.95E-05	40.575	0.000154	-15.981	0.000131	132.8803	0.000532	54.33875	0.000341	156.4678	0.000129	64.77788	0.000116	
-9.005	0.000115	33.547	9.45E-05	-12.602	9.61E-05	35.491	0.00016	-11.569	0.000141	143.0447	0.000543	28.65363	0.000333	140.3994	0.000128	39.0938	0.000113	
-4.968	0.000122	29.861	9.92E-05	-8.493	9.95E-05	30.611	0.000169	-7.251	0.000144	151.6556	0.000538	2.34725	0.000315	125.473	0.000124	17.80475	0.000108	
-0.997	0.000126	26.215	0.000106	-4.577	0.000103	25.879	0.000174	-3.086	0.000146	159.0104	0.000548	-15.1804	0.000319	111.9859	0.000123	-2.1095	0.0001	
2.826	0.000131	22.681	0.000104	-0.809	0.000109	21.331	0.000178	0.874	0.000147	165.2863	0.000543	-22.3175	0.00031	99.72743	0.000122	-16.1713	9.69E-05	
6.415	0.000133	19.325	0.000107	2.877	0.00011	17.007	0.000177	4.69	0.000153	170.4624	0.000539			83.46788	0.000117	-23.9161	9.79E-05	
9.718	0.000134	16.003	0.000111	6.394	0.000115	12.925	0.000181	8.358	0.000154	174.8339	0.000556			64.81094	0.000115	-27.5455	9.92E-05	
12.775	0.000134	12.832	0.00011	9.714	0.000117	9.076	0.000183	11.818	0.000154	179.0279	0.000549			46.18181	0.000113			
15.629	0.000136	9.839	0.000111	12.848	0.000115	5.457	0.000179	15.087	0.000156	183.0118	0.000594			25.83125	0.000108			
18.311	0.000138	6.899	0.000115	15.826	0.000116	2.071	0.000183	18.179	0.000157	186.2141	0.000628			7.45512	0.000105			
23.033	0.000138	4.083	0.000114	18.652	0.000116	-1.107	0.000183	21.089	0.000158	188.9816	0.000639			-5.17219	0.000104			
27.379	0.000141	1.459	0.000112	21.343	0.000119	-4.001	0.00018	23.829	0.00016	191.4355	0.00068			-14.8293	9.86E-05			
29.162	0.000143	-1.008	0.000113	23.941	0.00012	-6.709	0.000185	26.4	0.000159	194.0336	0.000701			-23.8459	0.000102			
31.051	0.000148	-3.354	0.000113	26.384	0.00012	-9.213	0.000179	36.341	0.000158	196.4514	0.001036			-28.6856	9.52E-05			
32.983	0.000138	-5.61	0.000115	31.654	0.000123	-11.516	0.000181	45.611	0.000164									
34.69	0.000135	-7.726	0.000113	36.623	0.000124	-13.7	0.000188	46.72	0.000167									
36.302	0.000141	-9.689	0.000112	38.298	0.000126	-15.714	0.000183	47.76	0.000165									
37.866	0.000139	-11.53	0.000111	39.892	0.000127	-17.56	0.000185	48.722	0.000166									
39.305	0.000137	-13.252	0.000111	41.37	0.000125	-19.276	0.000183	49.612	0.000165									
40.689	0.000146	-14.928	0.000119	42.748	0.000129	-20.842	0.000179	53.645	0.000152									
41.999	0.000138	-16.501	0.000111	44.064	0.000129	-22.208	0.000171	57.386	0.000166									
43.187	0.00014	-17.927	0.000114	45.279	0.000127	-23.468	0.000185	57.659	0.000177									
44.308	0.000139	-19.326	0.000118	48.676	0.000132	-24.705	0.000187	57.907	0.000153									
45.378	0.000145	-20.633	0.000113	51.886	0.000146	-25.849	0.000184	58.13	0.000159									
46.408	0.000148	-21.788	0.00011	52.606	0.000133	-26.89	0.000183	58.719	0.00017									
47.371	0.000144	-22.879	0.000112	53.285	0.000151	-27.822	0.000178	59.391	0.000153									
48.264	0.000145	-23.942	0.000117	53.925	0.000138	-28.653	0.000178											
49.109	0.000149	-24.938	0.000114	54.51	0.000154	-29.438	0.000186											
49.906	0.000148	-25.839	0.000111	55.033	0.000135	-30.191	0.000186											
50.65	0.000152	-26.699	0.000115	55.535	0.000162	-30.885	0.000186											
51.371	0.000158	-27.493	0.000108	56.05	0.000156	-31.457	0.000156											
52.058	0.000157	-28.248	0.000118	56.47	0.000141	-32	0.000196											
52.681	0.000154	-28.955	0.000108	56.86	0.000168	-32.54	0.00018											
53.261	0.000159	-29.567	0.000111	57.271	0.000174	-33.028	0.000189											
53.804	0.000157	-30.197	0.000124	57.613	0.000143	-33.438	0.000146											
54.312	0.000163	-30.771	0.000103	57.938	0.000199	-33.529	0.00027											
54.797	0.000165	-31.252	0.000109	58.266	0.000172	-33.953	0.000245											
55.244	0.000167	-31.759	0.000121	58.53	0.000172	-34.606	0.000173											
55.66	0.000171	-32.218	0.000103	58.796	0.000212	-34.888	0.000161											
56.09	0.000196	-32.594	0.0001	59.081	0.000237	-35.155	0.000187											
56.209	0.000158	-33.019	0.000134	59.316	0.000168	-35.441	0.000195											
56.243	0.000119	-33.405	9.54E-05	59.498	0.000237	-35.722	0.000186											
56.526	0.000115	-33.692	9.99E-05	59.678	0.000218	-35.974	0.000193											
56.844	0.000153	-34.033	0.000127	59.917	0.000334	-36.192	0.000186											
57.118	0.000105	-34.318	8.13E-05			-36.864	0.000152											
57.33	0.000114	-34.523	9.99E-05															
57.553	0.000118	-34.785	0.000126															
57.796	0.000145	-35.013	8.34E-05															
58.012	0.000127	-35.202	0.000114															
		-35.412	0.000111															
		-35.568	7.63E-05															
		-35.743	0.000135															
		-35.924	9.38E-05															
		-36.025	6.8E-05															
		-36.175	0.000144															
		-36.323	8.6E-05															
		-36.472	0.000161															
		-36.631	9.93E-05															



This appendix shows examples of Excel sheet analyses that were used to evaluate the effectiveness of BaCrO<sub>4</sub> as an oxidizer of hydrogen gas. Some gas volume calculations were repeated using alternate methods to check for internal consistency. Hydrogen gas evolution from the LCCM flight test heat paper by itself (section B-1, figures B-1 and B-2) is compared with that of the heat paper initiated when in physical contact with BaCrO<sub>4</sub> (section B-2, figures B-3 through B-5).

18.65928	Vapor pressure of water at 21 °C torr	18.65928			
19.83688	Vapor pressure of water at 22 °C torr	19.83688			
19.60136	Vapor pressure of water at experimental temperature of 21.8 °C torr				
0.23885	Maximum volume of water vapor present at 21.8 °C in sample bottles std atm cc				
1.533645	Maximum volume of water vapor present at 21.8 °C in gas handling system and Min-K Cal std atm cc				
2.412	Mass of Flight Test Heat Paper used was 2.412 g - GPS97-8&9 LLS p. 1295				
1.562976	Mass of BaCrO4 in Flight Test Heat Paper used g - GPS97-8&9 LLS p. 1295				
0.607824	Mass of Zr in Flight Test Heat Paper used g - GPS97-8&9 LLS p. 1295				
0.2412	Mass of Glass Fiber in Flight Test Heat Paper used g - GPS97-8&9 LLS p. 1295				
2.412	Check of Flight Test Heat Paper Mass g				
4.5	Density of BaCrO4 is 4.50 g/cc				
0.347328	Volume of BaCrO4 cc				
6.52	Density of Zr is 6.52 g/cc				
0.093225	Volume of Zr cc				
2.196	Density of glass (silicon dioxide (vitreous)) g/cc				
0.109836	Volume of glass fiber in heat paper cc				
1.061	Steel burner pad preheated to 700 °C g - GPS97-8&9 LLS p. 1295				
0.395	Steel foil 0.003 inch thick preheated to 700 °C g - GPS97-8&9 LLS p. 1295				
7.87	Density of iron g/cc				
0.185006	Total volume of steel cc				
0.735395	Estimated total solid volume of all components inside Min-K calorimeter cc				
There is little evidence from the recorded pressure curve Data INSTR 9 9/21/2011 15_35_47 that the evolved gas reacted with the ash after ignition (See report text and figures - see also 21SEPTestCurveGroupInstrnc (Autosaved).xls Excel Workbook)					
Calculate the total amount of gas formed when the first and second sample bottles were closed, just before the desiccator was opened, and at the end of the experiment When the first sample bottle was closed the gas pressure in the Min-K cal was not known because of the reduced flow rates caused by the metering valve - see report text and figures					
This experiment was initiated with sample bottle SB A20SEP2011 closed - GPS97-8&9 LLS pp. 1299-1300 Sample bottle A20SEP2011 was opened and closed from nominally 89.997 to 93.397 seconds with a final pressure of 112.9716 torr - GPS97-8&9 LLS p. 1300 (See 21SEPTestCurveGroupInstrnc (Autosaved).xls Excel Workbook in Documents/26August2011GasEvolutionTEST folder on LS13294 - Pressure starts increasing again at 93.397 seconds on Sheet 2)					
7.60467	Transducer voltage at one atmosphere - Average of 6 readings V (VBGET LLS p. 6)	Time (s)	Pressure (torr)	Press Voltage	
1.13041	Transducer voltage when SB A20SEP2011 was closed from recorded data V - See Also GPS97-8&9 LLS p.1300	89.997	151.087	1.511798	
16	Time elapsed from start of program to initiation of pyrotechnic s	93.397	112.9716	1.13041	
93.397	Time elapsed from start of program to closing of SB A20SEP2011 s				
273.15	Temperature at 0 °C in Kelvin				
760	Gas pressure at one atmosphere torr				
112.9716	Digitally recorded gas pressure inside the sample bottle SB A20SEP2011 when closed at 93.397 s from start of program torr				
10	Physical volume of sample bottle SB A20SEP2011 cc				
21.8	Dry room air temperature when sample bottle SB A20SEP2011 was closed °C				
1.376602	Volume of gas in closed sample bottle SB A20SEP2011 at 93.397 s from start of program std atm cc - from program - See also GPS97-8&9 LLS p.1300				
26.0039	Physical volume of gas handling system excluding sample bottle and Min-K calorimeter cc GPS97-8&9 LLS p. 1265	Time (s)	Pressure (torr)	Press Voltage	
38.941	Physical volume of Min-K calorimeter (38.9410 cc) GPS97-8&9 LLS p. 1265	475.797	314.1094	3.143024	
74.9449	Physical volume of gas handling system plus sample bottle plus Min-K calorimeter cc GPS97-8&9 LLS p. 1265				
2380.42	Physical volume of desiccator and butyl tube used to expand the gas sample volume cc GPS97-8&9 LLS p. 1269				
3.143024	Maximum transducer voltage recorded electronically - measured 7 minutes and 56 seconds (475.797) seconds after the program was started shortly after MV2 was opened V				
3.12	Maximum transducer voltage recorded manually - measured 10 minutes and 14 seconds (614 seconds) after the program was started torr (GPS97-8&9 LLS p. 1300) V				
314.1094	Maximum gas pressure recorded electronically before opening desiccator valve BV7 - measured 475.979 seconds after the program was started torr				
311.8084	Maximum gas pressure recorded manually before opening desiccator valve BV7 - measured 614 seconds after the program was started torr				
24.57647	Gas present in GHSYS and Min-K Cal 475.797 seconds after the program was started std atm cc - GPS97-8&9 LLS p.1300 - SB B20SEP2011 is closed			24.57647	
25.95307	Total gas evolution amount measured at 475.797 seconds after the program was started before taking second gas sample std atm cc				

Figure B-1. Gas evolution of LCCM flight test heat paper.

Figure B-2. Gas evolution from LCCM flight test heat paper.

## B-2. Gas Evolution of LCCM Flight Test Heat Paper in Contact with BaCrO<sub>4</sub>

Times noted on this spreadsheet are referred to time zero (12.396 seconds after the data acquisition program start) unless otherwise noted				
14.69594	One Atmosphere psi			
101.325	One Atmosphere Pa			
8.314472	Molar Gas Constant J/mol-K (or Pa·m <sup>3</sup> /mol-K)	101.3251	joules/liter-atm	101.3295 101.3271
0.082057	Molar Gas Constant liter-atm/mol-K			
22.41398	Liters in one mole of an ideal gas at STP - V=nRT/P			
18.015	Molecular weight of water g			
Some data is reported to more significant figures than justified for convenience when working with Excel and to simplify mathematical debugging analyses				
18.6593	Vapor pressure of water at 21 °C torr		18.65928	
19.8369	Vapor pressure of water at 22 °C torr		19.83688	
19.8369	Vapor pressure of water at experimental temperature of 22.0 °C torr			
0.241556	Maximum volume of water vapor present in one sample bottle std atm cc			
0.000194	Maximum weight of water vapor present in sample bottles g			
18.015	Molecular weight of water g - check			
1.545071	Maximum possible volume of water vapor at 22.0 C in gas handling system and Min-K Cal containing heat paper ash and steel solids std atm cc - Does not include sample bottle			
2.028184	Maximum possible volume of water vapor in both sample bottles and gas handling system at 22.0 C std atm cc			
2.4224	Mass of Flight Test Heat Paper used was 2.4224 g - GPS97-889 LLS pp. 1336, 1340			
1.0950	Mass of BaCrO <sub>4</sub> powder used was 1.0950 g - GPS97-889 LLS pp. 1336, 1340			
0	Mass of NBS H-350-39 350 cal/g heat powder (~21/79 weight percent Zr/BaCrO <sub>4</sub> powder) used g - GPS97-889 LLS pp. 1336, 1340			
1.569715	Mass of BaCrO <sub>4</sub> powder in heat paper g - GPS97-889 LLS pp. 1336, 1340			
0	Mass of BaCrO <sub>4</sub> powder in heat powder g - GPS97-889 LLS pp. 1336, 1340			
2.664715	Total Mass of BaCrO <sub>4</sub> g			
4.5	Density of BaCrO <sub>4</sub> is 4.50 g/cc			
0.592159	Total volume of BaCrO <sub>4</sub> cc			
0.610445	Mass of Zr powder in heat paper g - GPS97-889 LLS pp. 1336, 1340			
0	Mass of Zr powder in heat powder g - GPS97-889 LLS pp. 1336, 1340			
0.610445	Total Mass of Zr present g			
6.52	Density of Zr is 6.52 g/cc			
0.093627	Total volume of Zr cc			
0.24224	Mass of glass fiber in heat paper g			
2.196	Density of glass (silicon dioxide (vitreous)) g/cc			
0.11031	Total volume of glass fiber in heat paper cc			
2.4224	Check of heat paper mass g			
0	Check of heat powder mass g			
1.0725	Steel burner pad ~1.125 inch diameter by ~0.140 inch thick preheated to 700 °C g - GPS97-889 LLS p. 1335			
0.3887	Steel foil ~1.125 inch diameter by 0.003 inch thick preheated to 700 °C g - GPS97-889 LLS p. 1336			
7.87	Density of iron g/cc			
0.185667	Total volume of steel cc			
0.981762	Estimated total solid volume of all components inside Min-K calorimeter before (and after) ignition cc			
The first sample bottle was labeled 07192012A - GPS97-889 LLS p.1340				
The second sample bottle was labeled 07192012B - GPS97-889 LLS p.1340				
Time zero used for the pressure-time curve was ~0.2 seconds before the initial pressure rise (12.396 seconds after the program start) - See bTR426JULY2012GETestGraph.xls in the Documents/TR4 folder of LS13294				
Times for closing the sample bottles are estimates because closing the sample bottles had no effect on the recorded pressure-time curve				
Calculate the total amount of gas present shortly before opening the the second sample bottle (867.001 s), when the second sample bottle was closed (807.6 s), just before the desiccator was opened (1149.8s), and at the end of the experiment (2445.3 s)				
When the first sample bottle was closed at ~99.6 s after time zero the gas pressure in the Min-K cal was not known because of the reduced flow rates caused by the metering valve - see report text and figures				
There is evidence from the recorded pressure curve Data INSTR 9 7_26_2012 14_26_06 that the evolved gas reacted with the solids throughout the experiment				
There is evidence from the recorded pressure curve Data INSTR 9 7_26_2012 14_26_06 that water vapor was removed by the ash at the experiment end without producing additional gas				
There is evidence from the recorded pressure curve Data INSTR 9 7_26_2012 14_26_06 that gas removal occurred after MV2 was fully opened at 524.9 s				
The recorded pressure-time curve Data INSTR 9 7_26_2012 14_26_06 is also shown in the Documents/PSC2012LS13294EEEEEF folder on LS13294 - See GPS97-889 LLS p. 1341				
(See report text and figures noted above - see also bTR426JULY2012GETestGraph.xls Excel Workbook in Documents/TR4 folder on LS13294)				
The data suggests that significant amounts of hydrogen gas are not produced by the reaction of water (vapor or liquid) with the ash but further experimental confirmation of this is needed				

Figure B-3. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO<sub>4</sub>.

Figure B-4. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO<sub>4</sub>.

3.306403	Total volume of gas evolved measured at 807.6 s after time zero (Includes GHS, Min-K Cal, and both sample bottles) std atm cc - GPS97-889 LLS p.1340	
3.306403	Total volume of gas evolved measured at 807.6 s after time zero (Includes GHS, Min-K Cal, and both sample bottles) std atm cc - Alternate method - GPS97-889 LLS p.1340	
Some key electronically recorded time and pressure data from transducer voltages - See Excel workbook bTR426July2012GETestGraph.xls in Documents/TR4 folder on LS13294		
Time zero is taken as 12.396 seconds after the program start, and occurs ~0.1 second before the initial pressure rise		
Ignition is 15 seconds after program start as recorded manually by timer (12.396 s by pressure- time curve) -GPS97-889 LLS p. 1340 - See Excel workbook bTR426July2012GETestGraph.xls for all readings below		
Time (s)	Pressure (torr)	- See Excel workbook bTR426July2012GETestGraph.xls
0	0.04033	Time zero was measured electronically as 12.396 s after the program start and occurred ~0.1 s before the initial pressure rise
99.6	25.53642	Sample bottle 07192012A is closed -no measured effect on pressure - 1 minute 52 seconds by timer - GPS97-889 LLS p.1340
356.001	38.49133	Representative gas pressure shortly before removing sample bottle 07192012A and replacing with sample bottle 07192012B (MV2 is closed) - GPS97-889 LLS p.1340
517.3	40.24389	Metering valve MV2 was opened at ~517 seconds for equilibrium pressure readings with sample bottle 07192012B attached
524.9	42.56114	Near maximum electronic pressure recorded after opening metering valve MV2
667.001	39.86007	Gas pressure shortly before opening sample bottle 07192012B
675.6	34.99921	Gas pressure after opening sample bottle 07192012B - GPS97-889 LLS p.1340
807.6	33.25836	Gas pressure on closing sample bottle 07192012B - 13 minutes and 40 seconds (~820 seconds by manual timer reading) after program start GPS97-889 LLS p.1340
1078	30.62887	Close metering valve MV2 to avoid powder redistribution when BV7 to desiccator is opened (1078.0 s from time zero) - GPS97-889 LLS p.1340
1149.8	30.3101	Electronically recorded pressure shortly before opening BV7 to desiccator at ~19 minutes 25 s from program start by manual records - GPS97-889 LLS p.1340
1159.7	3.60401	Gas pressure after opening BV7 to desiccator - GPS97-889 LLS p.1340
1181.1	0.82619	Gas pressure after opening BV7 to desiccator - GPS97-889 LLS p.1340
1260.2	0.70909	MV2 was reopened at ~1260.2 seconds from the initial pressure rise - lowest pressure measured
1401.5	16.25316	Highest gas pressure recorded after reopening MV2 at end of experiment torr
2445.3	6.32848	Representative gas pressure on final plateau after opening BV7 and MV2 (and end of experiment)
0.306	Manual valve reading shortly before opening the valve BV7 to the desiccator at 1078 s (measured by timer from start of program) V - GPS97-889 LLS1340	
30.6	Manually read pressure shortly before the valve BV7 to the desiccator was opened torr - GPS97-889 LLS1340	
2.383395	Manually read volume of gas in Min-K calorimeter and gas handling system shortly before the desiccator valve BV7 was opened std atm cc - SB 07192012B is closed 2.383395	
2.383395	Manually read volume of gas in Min-K calorimeter and gas handling system shortly before the desiccator valve BV7 was opened std atm cc - SB 07192012B is closed - Alternate method	
3.093346	Manually read total volume of gas including both sample bottles shortly before opening valve to desiccator std atm cc	
30.3101	Electronically read pressure in torr just before the valve to the desiccator BV7 was opened 1149.8 s after time zero torr - See GPS97-889 LLS p. 1340	
2.360815	Electronically read volume of gas in Min-K calorimeter and gas handling system 1149.8 s after time zero just before the desiccator valve BV7 was opened std atm cc - SB208262011 is closed	
3.076766	Electronically read total volume of gas evolved 1149.8 s after time zero just before the desiccator valve BV7 was opened std atm cc - includes sample bottles	7.460738
18.83708	Total measured gas in GHS + Min-K Cal + Desiccator at 2445.3 s (at end of experiment) std atm cc	
19.55303	Total gas measured at 2445.3 seconds including gas in both sample bottles std atm cc	
16.47626	Apparent liquid water vaporized (with possible low temperature outgassing) in GHS+Min-K cal + Desiccator after gas expansion at 2445.3 seconds (total gas in system after expansion minus total gas in system before expansion) std atm cc	
2.028184	Maximum possible volume of water vapor in both sample bottles and gas handling system just before opening BV7 to the desiccator for gas expansion at 2445.3 seconds as shown above this sheet	
Total gas evolved summary		
3.41561	Maximum total gas evolution amount - measured at 667.001 seconds after the program was started std atm cc - GHS-Min-KCal-1SB	3.41561
3.306403	Total volume of gas evolved measured at 807.6 seconds including the gas in both sample bottles std atm cc - GPS97-889 LLS p.1340	3.306403
3.076766	Total gas evolved for the entire experiment measured at 1149.8 seconds shortly before expansion into the desiccator including both sample bottles std atm cc	3.076766
18.83708	Total measured gas in GHS + Min-K Cal + Desiccator at 2445.3 s (at end of experiment) std atm cc	
19.55303	Total evolved gas for the entire experiment measured at 2445.3 seconds std atm cc - includes both sample bottles, liquid water expanded to vapor and possible reactions with ash std atm cc	
		18.83708
1.270131	Total gas evolved for the entire experiment measured at 1149.8 seconds shortly before opening desiccator per gram of heat paper std atm cc	1.270131
8.071759	Total evolved gas for the entire experiment measured at 2445.3 seconds std atm cc/g of Flight Test Heat Paper - includes both sample bottles, liquid water expanded to vapor and possible reactions with ash	
15.76031	Apparent liquid water vaporized by gas expansion at 2445.3 seconds std atm cc	15.91444
0.241556	Maximum possible volume of water vapor present in each sample bottle std atm cc	
1.545071	Maximum possible volume of water vapor present in gas handling system and Min-K Cal std atm cc	
2.028184	Maximum possible volume of water vapor present in gas handling system, both sample bottles, and Min-K Cal at 22.0 C - Compare above this sheet - std atm cc	
0.432869	Total electronically measured gas present excluding water vapor at 1149.8 seconds from time zero including the gas in both sample bottles (07192012A and 07192012B) std atm cc/g of heat paper	
17.78849	Total water liquid plus vapor present measured at 2445.3 seconds std atm cc	
7.343335	Total water liquid plus vapor present measured at 2445.3 seconds std atm cc/g of Heat Paper - Last data point in experiment - MV2 and BV7 remain wide open	

Figure B-5. Gas evolution from LCCM flight test heat paper in physical contact with BaCrO<sub>4</sub>.

INTENTIONALLY LEFT BLANK.

---

## **Appendix C. Testing of Zr-based Gas Getters**

---

This appendix shows examples of Excel sheet analyses that were used to evaluate the effectiveness of Zr-based gas getters in atmospheres of pure hydrogen (section C-1, figure C-1) and in a hydrogen/air gas mixture (section C-2, figures C-2 and C-3). Some gas volume calculations were repeated using alternate methods to check for internal consistency.

## C-1. Hydrogen Gas Gettering from a Pure Hydrogen Atmosphere – Getter Tested as Received

13.9209	Measured physical volume of hydrogen source chamber cc (GPS97-8&9 LLS p. 1207, p. 1209)								
43.1748	Measured combined physical volume of hydrogen source and reaction chambers while containing sample boat and getter cc (GPS97-8&9 LLS p. 1209)								
23.61288	Estimated total physical volume of heated portion of the stainless steel tube in the tube furnace cc			23.61288		29.2539			
12.82675	Estimated physical volume of the stainless steel tube portion at 300 C cc								
10.78613	Estimated physical volume of the stainless steel tube portion with one end at room temperature and one end at 300 C cc								
160.55	Estimated (median) temperature of the gas in the stainless steel tube with one end at room temperature and one end at 300 C - in degrees C								
148.2936	Total amount of hydrogen used in test std atm cc	5.196	11.47546	148.2936	Total measured H2 0.1 s before initial pressure decline std atm cc				
19.56192	Estimated physical volume of gas that remained at room temperature cc								
1.423817	Amount of hydrogen that remained at room temperature after 10 seconds after To std atm cc								
0.4793	Amount of hydrogen at 300 C after 10 seconds after To std atm cc								
0.532642	Amount of hydrogen at 160.55 C in ends of stainless steel tube after 10 after To std atm cc								
10.65244	Total amount of hydrogen not gotten at 4.800 seconds after To std atm cc								
2.435759	Total amount of hydrogen not gotten at 10.001 seconds after To std atm cc			98.35747	Percentage of Hydrogen gotten 10.001 s after To				
0.203427	Total amount of hydrogen not gotten at 60 seconds after To std atm cc								
0.039884	Total amount of hydrogen not gotten at 133.4 seconds after To std atm cc								
11.47546	Initial pressure of hydrogen in source chamber atm	Summary of pressures (atm) vs time (s) (To ~0.1 s before getter is exposed to H2) - shown in this workbook sheet 2							
21.1	Temperature of source chamber and room C GPS97-8&9 LLS p. 1203	Getter was exposed to H2 at initial MKS pressure decline ~0.1 s after To where To = 5.196 s after program start							
300	Temperature of tube furnace C			s (from program start)	s (from To)	atm			
0.078408	Pressure of hydrogen gas at 10.001 seconds after To atm			5.196	0	11.47546			
0.006548	Pressure of hydrogen gas at 60 seconds after To atm			15.197	10.001	0.078408			
2.54	cm/inch	3.141593		25.096	19.9	0.021228			
273.15	deg K at 0 C			65.196	60	0.006548			
11	Length of heating elements in tube furnace inch			125.097	119.901	0.002054			
11	Estimated length of portion of the stainless steel tube at 300 C during test inch			138.596	133.4	0.001284			
14.25	Length of thermal insulation in tube furnace inch								
0.375	Outer diameter of stainless steel tube inch								
0.037	Wall thickness of stainless steel tube by calipers measurement inch								
0.301	Inner diameter of stainless steel tube inch								
3	Estimated length past thermal insulation for stainless steel tube to return to room temperature inch								
20.25	Estimated length of portion of the stainless steel tube heated above room temperature inch			20.25					
9.25	Estimated length of stainless steel tube with one end at 300 C and one end at room temperature - total of two ends inch					Pressure at 10.001 seconds if no hydrogen removed - torr			
23.875	Total measured length of stainless steel tube inch								
						4.773599	atm		
Volumes of the stainless steel boat and the getter are small (see estimates below) and are not included in the above volume calculations									
7.87	Density of iron g/cc	Summary of pressures (atm) from time of program start (s) - shown in this workbook sheet 2							
0.411	Mass of sample boat g GPS97-8&9 LLS p. 1199	(Getter was exposed to H2 ~ 5.196 s after program start)							
0.052224	Estimated volume of sample boat cc			s	atm				
				0	11.47632				
				9.996	0.342904	4.8	4.8		
6.52	Density of zirconium g/cc			59.996	0.007618				
2.029	Amount of getter used g GPS97-8&9 LLS p. 1199			119.996	0.002568				
0.311196	Estimated volume of getter cc			138.596	0.001284				
4.773599	Pressure at 10 seconds from program start if no hydrogen removed - atm								
3627.935	Pressure at 10 seconds from program start if no hydrogen removed - torr								
92.81665	Percent hydrogen removed by 4.800 seconds after To								
98.35747	Percent hydrogen removed by 10.001 seconds after To								
99.86282	Percent hydrogen removed by 60 seconds after To								
99.9731	Percent hydrogen removed by 133.4 seconds after To								

Figure C-1. Hydrogen gas gettering from a pure hydrogen atmosphere.



## C-2. Hydrogen Gas Gettering from a Hydrogen/Air Mixture

Basic Procedure									
The gas handling system (GHS) and stainless steel (SS) tube were first flushed and filled with helium to nominally 120 PSIG, then the getter was heated to 700 C under helium in the SS tube to drive off H2									
The SS tube was then allowed to cool to 300 C and sealed by closing BV2									
The GHS and sample bottle were then evacuated and flushed with H2, then H2 was stored in the 10 cc sample bottle by closing BV6 - VBGET LLS p.73a									
The GHS system was then evacuated and flushed with dry room air, next the SS tube was evacuated and sealed under a fore pump vacuum, then the GHS was flushed and filled with dry room air at 1 atm									
The GHS system was then sealed while containing dry room air at a pressure of 1 atm by closing BV8									
BV6 was then opened, allowing the H2 and air to mix for ~ 1 hour, then BV2 was opened and hydrogen/air mixture reacted with the getter material which had been held under vacuum at 300 C									
The pressure-time voltage trace shown in the report takes time zero ~0.1 second before the first pressure decline that occurred when BV2 was opened - 6.097 seconds after data recording actually began									
The sample bottle remained open during most of the experiment and was closed shortly before the pressure recording trace was stopped at 1558.5 seconds									
At 1558.5 seconds, the gas remaining in the system was 100% H2									
End Basic Procedure									
Volumes of the stainless steel boat and the getter are small and are not included in these volume calculations									
14.69594 Pressure of One Atmosphere (lb/in2)									
101325 Pressure of One Atmosphere Pa									
25000 Maximum pressure reading of MKS transducer torr									
10 Maximum output voltage of MKS transducer V									
760 Atmospheric pressure torr									
0.304 Transducer reading at one atmosphere V									
273.15 Absolute temperature K at 0 degrees C									
21.85 Room temperature during experiment was 21.85 C - VBGET LLS pp. 77-78									
300 Tube furnace temperature reading and temperature of ~11 inches of the 0.375 inch diameter SS tube that contained the getter in its central area during experiment C									
700 Tube furnace temperature reading and temperature of ~11 inches of the 0.375 inch diameter SS tube that contained the getter in its central area while cleaning getter surface C									
10 Physical volume of hydrogen in sample bottle cc									
3.0857 MKS manual readout for H2 in 10 cc sample bottle at room temperature before start of experiment V - VBGET LLS p.74									
7714.25									
10.15033									
93.98516 Volume of H2 used in experiment std atm cc									
26.0039 Measured internal volume of basic GHS cc - See VBGET LLS p. 9 and GPS97-88.9 LLS p. 1258, p. 1265									
24.07785 Volume of dry room air (dew point -56.3 C) used in experiment std atm cc									
20.39407 Volume percent of dry room air used in experiment									
118.063 Total gas used in experiment (hydrogen plus dry room air) std-atm-cc									
118.063									
1.0635 MKS manually measured transducer voltage just before BV2 was opened to expose the evacuated getter to the H2/air mixture at experiment start V - VBGET LLS p. 77									
3.498355 MKS manually measured pressure of gas just before BV2 was opened to expose the evacuated getter to the H2/air mixture at experiment start atm									
2658.75									
1332.118 MKS electronically measured pressure of gas recorded 1 second after time zero torr - see b14OCT2011GasGetCurve.xls in the Documents/26August2011GasEvolutionTest folder on LS13294									
Time zero for this test is taken at 6.097 seconds from the program start which is ~ 0.1 second before the pressure first started to decrease as shown in b14OCT2011GasGetCurve.xls									
1.752786 MKS electronically measured pressure of gas recorded 1 second after time zero atm (from b14OCT2011GasGetCurve.xls) in the Documents/26August2011GasEvolutionTest folder									
22.9375 Total length of the 0.375 inch OD SS tube used in the 14 October 2011 gas gettering test was 22 15/16 inch - VBGET LLS p. 60									
0.376 Measured outer diameter of the SS tube used in the 14 October 2011 gas gettering test inch - VBGET LLS p. 85									
0.035 Wall thickness of stainless steel tube as confirmed by calipers measurement in the 14 October 2011 gas gettering test inch									
See GasGetterUntreated12202010b.xls in TayanAlanson folder on LS13294 (0.035 inch is a standard wall thickness)									
0.306 Inner diameter of the SS tube used in the 14 October 2011 gas gettering test inch									
2.54 Centimeters per inch									
3.141593 Value of Pi									
3.141593									
110.916 Calculated mass of the SS tube with an 0.035 inch wall thickness g - compare with VBGET LLS p. 20, p. 22									
110.916									
7.87 Density of iron g/cc									

Figure C-2. Gas gettering from a hydrogen/air mixture.



NO. OF  
COPIES ORGANIZATION

1  
ELEC ADMNSTR  
DEFNS TECHL INFO CTR  
ATTN DTIC OCP  
8725 JOHN J KINGMAN RD STE 0944  
FT BELVOIR VA 22060-6218

1 US ARMY RSRCH DEV AND ENGRG  
CMND  
ARMAMENT RSRCH DEV & ENGRG  
CTR  
ARMAMENT ENGRG & TECHN LGY  
CTR  
ATTN AMSRD AAR AEF T J MATTS  
BLDG 305  
ABERDEEN PROVING GROUND MD  
21005-5001

3 CDR US ARMY TACOM ARDEC  
ATTN RDAR MEM C D TROAST  
BLDG 172  
PICATINNY ARSENAL NJ 0706-5000

1 MDA/DTFF  
ATTN C WILLIAMS  
BLDG 5222 MARTIN RD  
REDSTONE AL 35898

1 US ARMY ARDEC  
ATTN AMSRD AAR MEF S  
C MCMULLAN  
BLDG 407  
PICATINNY ARSENAL NJ 07806-5000

1 US ARMY ARDEC  
ATTN RDAR EIF C JANOW  
BLDG 6  
PICATINNY ARSENAL NJ 07806-5000

1 US ARMY ARDEC  
ATTN RDAR MEF E G SALATHE  
BLDG 94  
PICATINNY ARSENAL NJ 07806-5000

2 US ARMY ARDEC  
ATTN RDAR MEE T J PORET  
ATTN RDAR MEE T G CHEN  
BLDG 1515  
PICATINNY ARSENAL NJ 07806

1 US ARMY ARDEC  
ATTN RDAR MEF F B ARMSTRONG  
BLDG 6  
PICATINNY ARSENAL NJ 07806

NO. OF  
COPIES ORGANIZATION

2 US ARMY ARDEC  
ATTN RDAR MEF F K AMABILE  
ATTN RDAR MEF F R DRATLER  
BLDG 6  
PICATINNY ARSENAL NJ 07806-5000

1 US ARMY INFO SYS ENGRG CMND  
ATTN AMSEL IE TD A RIVERA  
FT HUACHUCA AZ 85613-5300

3 NAV SURFACE WARFARE CTR,  
CARDEROCK DIV  
ATTN CODE 616 C WINCHESTER  
ATTN P KELLER  
ATTN P SMITH  
9500 MACARTHUR BLVD  
BLDG 12D200  
WEST BETHESDA MD 20817-5700

3 NAVAL SURFACE WARFARE CENTER  
ATTN CODE 3626 D ROSENLOF  
ATTN CODE 3626 R NOLAN  
ATTN CODE 477400D C HINNERS  
CHINA LAKE CA 93555

1 NSWC CRANE  
ATTN GSXL B3287E S STUART  
300 HIGHWAY 361  
CRANE IN 47522-5001

1 NSWC DAHLGREN  
ATTN COCE G33 G WILES  
6210 TISDALE RD STE 223  
DAHLGREN VA 22448

1 WRIGHT LABORATORY  
AERO PROPULSION & POWER  
DIRECTORATE  
ATTN WL/POOS-2 D RYAN  
1950 FIFTH ST  
WRIGHT-PATTERSON AFB OH  
45433-7251

5 SANDIA NATIONAL LABORATORIES  
POWER SOURCES TECH GROUP  
ATTN E BRANSON  
ATTN A GRILLET  
ATTN D INGERSOL  
ATTN E PIEKOSATTN  
ATTN D WESOLOWSKI  
PO BOX 5800  
ALBUQUERQUE NM 87185-0613

NO. OF  
COPIES ORGANIZATION

1 US GOVERNMENT PRINT OFF  
DEPOSITORY RECEIVING SECTION  
ATTN MAIL STOP IDAD J TATE  
732 NORTH CAPITOL ST NW  
WASHINGTON DC 20402

1 RICHARD KULLBERG  
1942 CHEYENNE BLVD  
COLORADO SPRINGS CO 80906

2 ADVANCED THERMAL BATTERIES,  
INC  
ATTN D BRISCOE  
ATTN G CHAGNON  
107 BEAVER CT  
COCKEYSVILLE MD 21030

2 ASB  
ATTN J SWEENEY  
ATTN S SHOEFFERT  
BOURGES CEDEX  
ALLEE SAINTE HELENE 18021  
FRANCE

3 EAGLE PICHER TECHNOLOGIES,  
LLC  
ATTN C LAMB  
ATTN J FERRARO  
ATTN M STEELE  
PO BOX 47  
JOPLIN MO 64802

3 ENERSYS ADVANCED SYSTEMS  
ATTN D SWANSON  
ATTN P SCHISSELBAUER  
ATTN T HURST  
104 ROCK RD  
HORSHAM PA 19044

1 ELEC ILIKA TECHNOLOGIES  
EMTERPRISE ROAD  
ATTN G CARR  
UNIVERSITY OF SOUTHAMPTON  
SCIENCE PARK  
SOUTHAMPTON SO16 7NS  
UNITED KINGDOM

1 INVENTEK  
ATTN T KAUN  
320 WILLOW ST  
NEW LENOX IL 60451

1 LECLANCHE, S A  
ATTN P REUTSCHI  
48 AVENUE DE GRANDSON  
YVERDON-LES-BAIN CH-1401  
SWITZERLAND

NO. OF  
COPIES ORGANIZATION

1 OMNITEK PARTNERS, LLC  
ATTN R T MURRAY  
111 W MAIN STREET STE 112  
BAYSHORE NY 01706-8313

1 RAYTHEON MISSILE SYSTEMS  
ATTN D DICKHERBER  
TU BLDG 805 M/S C4  
1151 E HERMANN'S RD  
TUCSON AZ 85706

1 TECHNION  
ATTN N HAIMOVICH  
DEPT OF CHEM ENG  
HAIFA 32000  
ISRAEL

3 THE ENSER CORPORATION  
ATTN E DAYALAN  
ATTN J PUGH  
ATTN N SHUSTER  
5430 70TH AVE N  
PINELLAS PARK FL 33781-0707

22 HCS US ARMY RSRCH LAB  
4 CDS ATTN IMAL HRA  
2 PDFS MAIL & RECORDS MGMT  
ATTN RDRL CIO LL TECHL LIB  
ATTN RDRL CIO LT TECHL PUB  
ATTN RDEL SED C W BEHL  
ATTN RDRL SED C M S DING  
(2 CDS)  
ATTN RDRL SED C  
F KRIEGER (10 HCS, 2 CDS, 2 PDFS)  
ATTN RDRL SED C C LUNDGREN  
ATTN RDRL SED C J SWANK  
ATTN RDRL SED E SHAFFER  
ATTN RDRL SED J HOPKINS  
ATTN RDRL SES A J PRICE  
ATTN RDRL SES S A LADAS  
ATTN RDAR MEF FA D ERRERA  
ATTN RDAR MEF FA W KONICK  
ADELPHI MD 20783-1197

TOTAL: 80 (70 HCS, 2 ELEC, 4 CDS, 4 PDFS)